# Investigating Executive Function and its various facets through the lens of Bilingualism

*A thesis to be submitted to Indian Institute of Technology, Guwahati, in partial fulfilment for the degree of Doctor of Philosophy*


*Submitted by*

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# DECLARATION

I hereby declare that the thesis entitled, **"Investigating Executive Function and its various facets through the lens of Bilingualism"** is my original work carried out in Centre for Linguistic Science and Technology, Indian Institute of Technology, Guwahati, under the joint supervision of Prof. Bidisha Som, Department of Humanities and Social Sciences and Centre for Linguistic Science and Technology, IIT Guwahati and Dr. Abhishek Shrivastava, Department of Design and Centre for Linguistic Science and Technology, IIT Guwahati. Any material used from other sources have been duly credited with appropriate citation and references. I also affirm, to the best of my knowledge, that no part of this thesis has been plagiarised, and will take full responsibility should a complaint arise.

Emily Thomas

14th April, 2025

# CERTIFICATE

This is to certify that the thesis entitled **"Investigating Executive Function and its various facets through the lens of Bilingualism"** submitted by Emily Thomas in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy to Indian Institute of Technology, Guwahati, embodies bonafide record of research work carried out under our joint supervision at the Centre for Linguistic Science and Technology, IIT Guwahati. All work in this study has been carried out by Emily Thomas herself and has not been submitted to any other institute or university for any degree or diploma.

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To my younger brother Kevin (Neeni to me and only me), I am still waiting for a reply to that text I sent, just so you know. Milo, you cutie, you're a dog, so probably won't ever read this, but thank you for being so dang adorable all the time. I miss you every single day.

Finally, to my younger self, especially when I was most unkind to you, I wish I could go back in time and tell that little girl all that I am capable of, all that I did. This? This is just the beginning.

Emily Thomas
14th April, 2025

# Abstract

This thesis explores how bilinguals' real-world language use—particularly their contextual patterns of language switching—modulates executive control functions. Framed within the Adaptive Control Hypothesis, the study investigates the cognitive implications of bilingual interactional contexts (single-language, dual-language, and dense code-switching) on the components of the executive control mechanism, namely, cognitive flexibility, working memory, inhibitory control, and affective control. In order to do so, a comprehensive battery of nine behavioural tasks (such as Switching tasks, *N*-Back task, Stroop task, Emotional Go/No-go task, etc.) was employed to target the various domains of executive control. The participants were grouped based on their contextual language usage, and their performance in the abovementioned tasks was analysed. The analyses examined both accuracy and reaction time measures to see how different components of the executive control engage across various tasks, based on the language usage behaviour of young adult bilinguals. Our findings indicated that all three language context environments exerted differential patterns of cognitive control, thereby resulting in the language context groups performing differently across the various tasks. This suggests that contextual language use does not maintain a uniform advantage as previously assumed, but rather contextual usage shapes the utilisation of executive control mechanisms in a context and domain-specific manner. Thus, by situating bilingualism within its sociolinguistic context, this study contributes to a better understanding of bilingualism in an under-researched non-WEIRD country where being bilingual is commonplace and the norm.

# Table of Contents


**List of figures** i

**List of tables** v

**List of Abbreviations** ix

**1 Introduction** **1**

1.1 Introduction 2

1.2 Chapter overview 5

1.3 Human cognition: Executive Control Mechanisms 5

1.4 Cognition and Bilingualism 9

1.5 Bilingualism in the Indian context 21

1.6 Rationale of the present study 25

1.7 Research aim, Questions and Hypothesis 26

1.8 Overview of the thesis structure 27

1.9 Chapter summary 28

**2 Literature review** **29**

2.1 Introduction 30

2.2 Chapter Overview 30

2.3 Bilingualism and Executive Control 30

2.4 Research Gaps 54

2.5 Chapter summary 55

**3 Methodology** **57**

3.1 Introduction 58

3.2 Chapter overview 58

3.3 Participants 59

3.4 Questionnaires 59

3.5 Tools 63

3.6 General Procedure 64

3.7 Tasks 64

3.8 Stimuli 71

3.9 Data 72

3.10 Ethics 72

3.11 Chapter summary 73

**4 Bilingualism and Task Switching** **75**

4.1 Introduction 76

| | | | |
|---|---|---|---|
| | 4.2 | Chapter overview | 78 |
| | 4.3 | Objective and Hypothesis | 78 |
| | 4.4 | Experiment 1 | 79 |
| | 4.5 | Experiment 2 | 95 |
| | 4.6 | Discussion | 169 |
| | 4.7 | Chapter summary | 170 |
| **5** | **Bilingualism and Working memory** | | **173** |
| | 5.1 | Introduction | 174 |
| | 5.2 | Chapter overview | 174 |
| | 5.3 | Objective and Hypothesis | 175 |
| | 5.4 | N-Back task | 175 |
| | 5.5 | Discussion | 188 |
| | 5.6 | Chapter summary | 188 |
| **6** | **Bilingualism and Inhibition** | | **191** |
| | 6.1 | Introduction | 192 |
| | 6.2 | Chapter overview | 192 |
| | 6.3 | Objective and Hypothesis | 193 |
| | 6.4 | Simon task | 193 |
| | 6.5 | Stroop task | 208 |
| | 6.6 | Go/No-go task | 220 |
| | 6.7 | Discussion | 226 |
| | 6.8 | Chapter summary | 227 |
| **7** | **Bilingualism and Affective control** | | **229** |
| | 7.1 | Introduction | 230 |
| | 7.2 | Chapter overview | 231 |
| | 7.3 | Objective and Hypothesis | 231 |
| | 7.4 | Emotional Stroop task | 231 |
| | 7.5 | Emotional Go/No-go task | 244 |
| | 7.6 | Discussion | 257 |
| | 7.7 | Chapter summary | 258 |
| **8** | **Conclusion** | | **261** |
| | 8.1 | Introduction | 262 |
| | 8.2 | Findings from the Experiments | 263 |
| | 8.3 | Implications of the findings | 267 |

8.4 Problems and Limitations 270

8.5 Future directions 271

**References** **273**

**Appendices** **303**

# List of figures

**Chapter 1**
***Figure 1.4.1:*** *Language mode continuum flowchart* 12

***Figure 1.4.2:*** *Architecture of the Adaptive Control Hypothesis* 14

***Figure 1.5.1:*** *Indian maps as per the distribution of the language families* 23

**Chapter 3**
***Figure 3.5.1:*** *Chronos device used for response recording* 63

***Figure 3.7.1:*** *Schematic diagram of a Univalent Switching Task.* 65

***Figure 3.7.2:*** *Schematic diagram of a Bivalent Switching Task.* 67

**Chapter 4**
***Figure 4.4.1:*** *Schematic representation of the practice session of the bivalent numbers switching task* 81

***Figure 4.4.2:*** *Schematic representation of the main session of the bivalent numbers switching task* 82

***Figure 4.4.3:*** *Group-wise EM Means based on LC in overall performance in bivalent numbers task* 87

***Figure 4.4.4:*** *Group-wise EM Means based on task-wise performance in bivalent numbers task* 88

***Figure 4.4.5:*** *Graph showing error analysis of bivalent numbers task* 91

***Figure 4.4.6:*** *Error analysis of each LC group in bivalent numbers task performance* 91

***Figure 4.5.1:*** *Schematic diagram of Univalent task performed.* 96

***Figure 4.5.2:*** *Schematic diagram of Bivalent task performed.* 97

***Figure 4.5.3:*** *Group-wise EM Means performance based on LC of overall performance in univalent task* 102

***Figure 4.5.4:*** *Group-wise EM Means performance based on task condition of overall performance in univalent task* 104

***Figure 4.5.5:*** *Interaction of LC × Task condition of overall performance in univalent task* 106

***Figure 4.5.6:*** *Graph showing error analysis of overall performance in univalent task* 108

***Figure 4.5.7:*** *Error analysis of each LC group in overall performance in univalent task* 109

***Figure 4.5.8:*** *Group-wise EM Means performance based on LC of local switch cost performance in univalent task* 114

***Figure 4.5.9:*** *Group-wise EM Means performance based on trial type of local switch cost in univalent task* 116

***Figure 4.5.10:*** *Interaction of LC × Task condition of local switch cost performance in univalent task* 118

***Figure 4.5.11:*** *Graph showing error analysis of local switch cost performance in univalent task* 120

***Figure 4.5.12:*** *Error analysis of each LC group of local switch cost performance in univalent task* 120

***Figure 4.5.13:*** *Group-wise EM Means performance based on LC of global switch cost performance in univalent task* 126

***Figure 4.5.14:*** *Group-wise EM Means performance based on task condition of global switch cost in univalent task* 127

***Figure 4.5.15:*** *Interaction of LC × Task condition of global switch cost performance in univalent task.* 129

***Figure 4.5.16:*** *Graph showing error analysis of overall performance in global switch cost in univalent task* 132

***Figure 4.5.17:*** *Error analysis of each LC group in overall performance in global switch cost in univalent task* 132

***Figure 4.5.18:*** *Group-wise EM Means performance based on LC of overall performance in bivalent task* 138

***Figure 4.5.19:*** *Group-wise EM Means performance based on task condition of overall performance in bivalent task* 139

***Figure 4.5.20:*** *Interaction of LC x Task condition of overall performance in bivalent task.* 142

***Figure 4.5.21:*** *Graph showing error analysis of overall performance in bivalent task* 144

***Figure 4.5.22:*** *Error analysis of each LC group of overall performance in bivalent task* 144

***Figure 4.5.23:*** *Group-wise EM Means performance based on LC of local switch cost performance in bivalent task* 150

***Figure 4.5.24:*** *Group-wise EM Means performance based on trial types of local switch cost in bivalent task* 151

***Figure 4.5.25:*** *Interaction of LC x Task condition of local switch cost performance in bivalent task* 154

***Figure 4.5.26:*** *Graph showing error analysis of local switch cost performance in bivalent task* 156

***Figure 4.5.27:*** *Error analysis of each LC group of local switch cost performance in bivalent task* 156

***Figure 4.5.28:*** *Group-wise EM Means performance based on LC of global switch cost performance in bivalent task* 161

***Figure 4.5.29:*** *Group-wise EM Means performance based on task condition of global switch cost in bivalent task.* 162

***Figure 4.5.30:*** *Interaction of LC x Task condition of global switch cost performance in bivalent task* 165

***Figure 4.5.31:*** *Graph showing error analysis of global switch cost performance in bivalent task* 167

***Figure 4.5.32:*** *Error analysis of each LC group of global switch cost performance in bivalent task* 167

**Chapter 5**

***Figure 5.4.1:*** *Schematic diagram of N-Back task performed.* 176

***Figure 5.4.2:*** *Group-wise EM Means performance based on Language Context in N-Back task* 180

***Figure 5.4.3:*** *Group-wise EM Means performance based on task condition in N-Back task performance* 181

***Figure 5.4.4:*** *Interaction of LC x Task condition in N-Back task performance.* 183

***Figure 5.4.5:*** *Error analysis of each LC group in N-Back task performance* 185

***Figure 5.4.6:*** *Graph showing error analysis of N-Back task performance* 186

**Chapter 6**

***Figure 6.4.1:*** *Schematic diagram of Simon task performed.* 194

***Figure 6.4.2:*** *Group-wise EM Means performance based on Language Context in Simon task performance* 199

***Figure 6.4.3:*** *Group-wise EM Means performance based on task condition in Simon task performance* 200

***Figure 6.4.4:*** *Interaction of LC x Task condition in Simon task performance.* 202

***Figure 6.4.5:*** *Error analysis of each LC group in Simon task performance* 204

***Figure 6.4.6:*** *Graph showing error analysis of Simon task performance* 205

***Figure 6.5.1:*** *Schematic diagram of Stroop task performed* 209

***Figure 6.5.2:*** *Group-wise EM Means performance based on Language Context in Stroop task performance* 213

***Figure 6.5.3:*** *Group-wise EM Means performance based on task condition in Stroop task performance* 215

***Figure 6.5.4:*** *Interaction of LC x Task condition in Stroop task performance.* 216

***Figure 6.5.5:*** *Error analysis of each LC group in Stroop task performance* 218

***Figure 6.5.6:*** *Graph showing error analysis of Stroop task performance* 218

***Figure 6.6.1:*** *Schematic diagram of Go/No-go task performed* 220

***Figure 6.6.2:*** *Group-wise EM Means performance based on Language Context in Go/No-go task* 223

***Figure 6.6.3:*** *Error analysis of each LC group in Go/No-go task performance* 225

***Figure 6.6.4:*** *Graph showing error analysis of Go/No-go task performance* 225

**Chapter 7**

***Figure 7.4.1:*** *Schematic diagram of Emotional Stroop task performed.* 233

***Figure 7.4.2:*** *Group-wise EM Means performance based on LC in Emotional Stroop task performance.* 237

***Figure 7.4.3:*** *Group-wise EM Means performance based on task condition in Emotional Stroop task performance* 238

***Figure 7.4.4:*** *Interaction of LC × Task condition in Emotional Stroop task performance* 240

***Figure 7.4.5:*** *Error analysis of each LC group in Emotional Stroop task performance.* 242

***Figure 7.4.6:*** *Graph showing error analysis of Emotional Stroop task performance* 242

***Figure 7.5.1:*** *Emotion faces used for Emotional Go/No-Go practice trials* 245

***Figure 7.5.2:*** *Schematic diagram of Emotional Go/No-Go task* 245

***Figure 7.5.3:*** *Group-wise EM Means performance based on LC in Emotional Go/No-go task performance* 248

***Figure 7.5.4:*** *Group-wise EM Means based on Emotion displayed in stimulus in Emotional Go/No-go task* 250

***Figure 7.5.5:*** *Interaction of LC × Emotion × Gender of the stimulus displayed in Emotional Go/No-go task* 253

***Figure 7.5.6:*** *Error analysis of LC × Emotion displayed in stimulus in Emotional Go/No-go task performance* 256

***Figure 7.5.7:*** *Graph showing error analysis of LC × Emotion displayed in stimulus in Emotional Go/No-go task* 256

# List of tables

**Chapter 1**

***Table 1.4.1:*** *Cognitive control processes and interactive contexts* 15

**Chapter 3**

***Table 3.3.1:*** *Brief description of tasks, participants and their age range* 59

**Chapter 4**

***Table 4.4.1:*** *LMM results of RT analysis of bivalent numbers task* 84

***Table 4.4.2:*** *Type III ANOVA Table with Satterthwaite's method of bivalent numbers task* 85

***Table 4.4.3:*** *Group-wise EM Means based on LC in overall performance in bivalent numbers task* 86

***Table 4.4.4:*** *Pair-wise analysis based on LC in overall performance in bivalent numbers task.* 87

***Table 4.4.5:*** *Group-wise EM Means based on task condition in overall performance in bivalent numbers task* 88

***Table 4.4.6:*** *Pair-wise analysis based on task condition in overall performance in univalent task.* 88

***Table 4.4.7:*** *GLMM results of error analysis of bivalent numbers task* 90

***Table 4.4.8:*** *LMM results of post-error performance in bivalent numbers task* 92

***Table 4.5.1:*** *LMM results of RT analysis of overall performance in univalent task* 100

***Table 4.5.2:*** *Type III ANOVA with Satterthwaite's method of overall performance in univalent task.* 101

***Table 4.5.3:*** *Group-wise EM Means based on Language Context of overall performance in univalent task.* 102

***Table 4.5.4:*** *Pair-wise analysis based on Language context of overall performance in univalent task.* 103

***Table 4.5.5:*** *Group-wise EM Means based on task condition of overall performance in univalent task.* 103

***Table 4.5.6:*** *Pair-wise analysis based on task condition of overall performance in univalent task.* 104

***Table 4.5.7:*** *Group-wise EM Means based on LC × task condition interaction of overall performance in univalent task.* 105

***Table 4.5.8:*** *GLMM results of error analysis of overall performance in univalent task* 107

***Table 4.5.9:*** *LMM results of post-error performance of overall performance in univalent task* 110

***Table 4.5.10:*** *LMM results of RT analysis of local switch cost performance in univalent task* 112

***Table 4.5.11:*** *Type III ANOVA table with Satterthwaite's method groups of local switch cost performance in univalent task.* 113

***Table 4.5.12:*** *Group-wise EM Means based on LC of local switch cost performance in univalent task* 114

***Table 4.5.13:*** *Pair-wise analysis based on LC local switch cost performance in univalent task* 115

***Table 4.5.14:*** *Group-wise EM Means based on trial type of local switch cost performance in univalent task* 115

***Table 4.5.15:*** *Table with pair-wise analysis based on trial type of local switch cost performance in univalent task* 116

***Table 4.5.16:*** *Table with group-wise EM Means based LC × trial type interaction of local switch cost performance in univalent task* 117

***Table 4.5.17:*** *GLMM results of error analysis of local switch cost performance in univalent task* 119

***Table 4.5.18:*** *LMM results of post-error performance of local switch cost performance in univalent task* 121

***Table 4.5.19:*** *LMM results of RT analysis of global switch cost performance in univalent task* 123

**Table 4.5.20:** *Type III ANOVA with Satterthwaite's method of global switch cost performance in univalent task* 125

**Table 4.5.21:** *Group-wise EM Means based on LC of global switch cost performance in univalent task.* 125

**Table 4.5.22:** *Pair-wise analysis based on LC of global switch cost performance in univalent task* 126

**Table 4.5.23:** *Group-wise EM Means based on task condition of global switch cost performance in univalent task* 127

**Table 4.5.24:** *Pair-wise analysis based on task condition of global switch cost performance in univalent task* 128

**Table 4.5.25:** *Group-wise EM Means based on LC × task condition interaction of global switch cost performance in univalent task.* 128

**Table 4.5.26:** *GLMM results of error analysis of global switch cost performance in univalent task* 131

**Table 4.5.27:** *LMM results of post-error performance of global switch cost performance in univalent task* 133

**Table 4.5.28:** *LMM results of RT analysis of overall performance in bivalent task* 135

**Table 4.5.29:** *Type III ANOVA with Satterthwaite's method of overall performance in bivalent task* 137

**Table 4.5.30:** *Group-wise EM Means based on LC of overall performance in bivalent task* 137

**Table 4.5.31:** *Pair-wise analysis based on LC of overall performance in bivalent task* 138

**Table 4.5.32:** *Group-wise EM Means based on task condition of overall performance in bivalent task* 139

**Table 4.5.33:** *Pair-wise analysis based on task condition of overall performance in bivalent task* 140

**Table 4.5.34:** *Group-wise EM Means based on LC × condition interaction of overall performance in bivalent task* 141

**Table 4.5.35:** *GLMM results of error analysis of overall performance in bivalent task* 143

**Table 4.5.36:** *LMM results of post-error performance of overall performance in bivalent task* 145

**Table 4.5.37:** *LMM results of RT analysis of local switch cost performance in bivalent task* 147

**Table 4.5.38:** *Type III ANOVA with Satterthwaite's method of local switch cost performance in bivalent task* 148

**Table 4.5.39:** *Group-wise EM Means based on LC of local switch cost performance in bivalent task* 149

**Table 4.5.40:** *Pair-wise analysis based on LC local switch cost performance in bivalent task.* 150

**Table 4.5.41:** *Group-wise EM Means based on trial type of local switch cost performance in bivalent task* 151

**Table 4.5.42:** *Pair-wise analysis based on trial type of local switch cost performance in bivalent task* 152

**Table 4.5.43:** *Group-wise EM Means based on LC × trial type interaction of local switch cost in bivalent task* 152

**Table 4.5.44:** *GLMM results of error analysis of local switch cost performance in bivalent task* 155

**Table 4.5.45:** *LMM results of post-error performance of local switch cost performance in bivalent task* 157

**Table 4.5.46:** *LMM results of RT analysis of global switch cost performance in bivalent task* 159

**Table 4.5.47:** *Type III ANOVA with Satterthwaite's method of global switch cost performance in bivalent task* 160

**Table 4.5.48:** *Group-wise EM Means based on LC of global switch cost performance in bivalent task.* 160

**Table 4.5.49:** *Pair-wise analysis based on LC of global switch cost performance in bivalent task* 161

**Table 4.5.50:** *Group-wise EM Means based on task condition of global switch cost performance in bivalent task* 162

**Table 4.5.51:** *Pair-wise analysis based on task condition of global switch cost performance in bivalent task.* 163

**Table 4.5.52:** *Group-wise EM Means of LC × task condition interaction of global switch cost in bivalent task.* 164

**Table 4.5.53:** *GLMM results of error analysis of global switch cost performance in bivalent task* 166

***Table 4.5.54:*** *LMM results of post-error performance of global switch cost performance in bivalent task* 168

**Chapter 5**

***Table 5.4.1:*** *LMM results of RT analysis of N-Back task performance* 177

***Table 5.4.2:*** *Type III ANOVA with Satterthwaite's method for N-Back task performance.* 179

***Table 5.4.3:*** *Group-wise EM Means based on LC in N-Back task performance* 179

***Table 5.4.4:*** *Pair-wise analysis based on LC in N-Back task performance* 180

***Table 5.4.5:*** *Group-wise EM Means based on task condition in N-Back task.* 181

***Table 5.4.6:*** *Pair-wise analysis based on task condition in N-Back task performance.* 182

***Table 5.4.7:*** *Group-wise EM Means based on LC x task condition interaction in N-Back task performance* 182

***Table 5.4.8:*** *GLMM results of error analysis of N-Back task performance* 184

***Table 5.4.9:*** *LMM analysis of post-error performance in N-Back task performance* 187

**Chapter 6**

***Table 6.4.1:*** *LMM results of RT analysis of Simon task* 196

***Table 6.4.2:*** *Type III ANOVA with Satterthwaite's method of Simon task performance* 197

***Table 6.4.3:*** *Group-wise EM Means based on LC in Simon task* 198

***Table 6.4.4:*** *Pair-wise analysis based on LC in Simon task* 199

***Table 6.4.5:*** *Group-wise EM Means based on task condition in Simon task performance.* 200

***Table 6.4.6:*** *Pair-wise analysis based on task condition in Simon task performance.* 201

***Table 6.4.7:*** *Group-wise EM Means based on LC x task condition interaction in Simon task performance* 202

***Table 6.4.8:*** *GLMM results of error analysis of Simon task performance* 203

***Table 6.4.9:*** *LMM results of post-error performance in Simon task performance* 205

***Table 6.5.1:*** *LMM results of RT analysis of Stroop task* 210

***Table 6.5.2:*** *Type III ANOVA with Satterthwaite's method for Stroop task performance* 211

***Table 6.5.3:*** *Group-wise EM Means based on LC in Stroop task performance* 212

***Table 6.5.4:*** *Pair-wise analysis based on LC in Stroop task performance* 213

***Table 6.5.5:*** *Group-wise EM Means based on task condition in Stroop task performance.* 214

***Table 6.5.6:*** *Pair-wise analysis based on task condition in Stroop task performance.* 215

***Table 6.5.7:*** *Group-wise EM Means based on LC x task condition interaction in Stroop task performance* 215

***Table 6.5.8:*** *GLMM results of error analysis of Stroop task performance* 217

***Table 6.5.9:*** *LMM results of post-error performance in Stroop task performance* 219

***Table 6.6.1:*** *LMM results of RT analysis of Go/No-go task performance* 222

***Table 6.6.2:*** *Type III ANOVA with Satterthwaite's method for Go/No-go task performance* 222

***Table 6.6.3:*** *Group-wise EM Means based on LC in Go/No-go task performance* 222

***Table 6.6.4:*** *Pair-wise analysis based on LC in Go/No-go task performance* 223

***Table 6.6.5:*** *GLMM results of error analysis of Go/No-go task performance* 224

**Chapter 7**


***Table 7.4.1:*** *Word list for Emotional Stroop task.* 232

***Table 7.4.2:*** *LMM analysis results of Emotional Stroop task* 234

***Table 7.4.3:*** *Type III ANOVA with Satterthwaite's method for Emotional Stroop task performance* 235

***Table 7.4.4:*** *Group-wise EM Means based on LC in Emotional Stroop task performance* 236

***Table 7.4.5:*** *Pair-wise analysis based on LC in Emotional Stroop task performance* 237

***Table 7.4.6:*** *Group-wise EM Means based on task condition in Emotional Stroop task performance* 238

***Table 7.4.7:*** *Pair-wise analysis based on task condition in Emotional Stroop task performance* 239

***Table 7.4.8:*** *Group-wise EM Means based on LC × task condition interaction in Emotional Stroop task* 241

***Table 7.4.9:*** *GLMM results of error analysis of Emotional Stroop task performance.* 241

***Table 7.4.10:*** *LMM results of post-error performance in Emotional Stroop task performance* 243

***Table 7.5.1:*** *LMM results of RT analysis of Emotional Go/No-go task performance* 246

***Table 7.5.2:*** *Type III ANOVA with Satterthwaite's method for Emotional Go/No-go task performance* 247

***Table 7.5.3:*** *Group-wise EM Means based on LC in Emotional Go/No-go task performance* 248

***Table 7.5.4:*** *Pair-wise analysis based on LC in Emotional Go/No-go task performance.* 248

***Table 7.5.5:*** *Group-wise EM Means of Emotion displayed in stimulus in Emotional Go/No-go task* 249

***Table 7.5.6:*** *Pair-wise analysis based on Emotion displayed in stimulus in Emotional Go/No-go task* 250

***Table 7.5.7:*** *Group-wise EM Means based on LC × Emotion displayed in stimulus in Emotional Go/No-go task* 250

***Table 7.5.8:*** *Group-wise EM Means based on Gender of the stimulus displayed in Emotional Go/No-go task* 251

***Table 7.5.9:*** *Pair-wise analysis based on Gender of the stimulus displayed in Emotional Go/No-go task* 251

***Table 7.5.10:*** *Group-wise EM Means based on LC × Gender of stimulus displayed in Emotional Go/No-go task* 252

***Table 7.5.11:*** *Group-wise EM Means of LC × Emotion × Gender of stimulus in Emotional Go/No-go task* 252

***Table 7.5.12:*** *GLMM table of error analysis of Emotional Go/No-go task performance* 254


**Chapter 8**


***Table 8.2.1:*** *Summary of findings from the experiments, including participants, tasks performed and results* 264

# List of Abbreviations

| Abbreviation | Phrase |
|---|---|
| **A** | Alternate (task condition) |
| **ACH** | Adaptive Control Hypothesis |
| **ANOVA** | Analysis of Variance |
| **CSC** | Code-Switching Context |
| **DCS** | Dense Code-Switching |
| **DLC** | Dual Language Context |
| **GLMM** | Generalized Linear Mixed Model |
| **L1** | First Language |
| **L2** | Second Language |
| **LC** | Language Context |
| **LMM** | Linear Mixed Model |
| **M** | Mixed (task condition) |
| **RT** | Reaction Time (or Response Time) |
| **SLC** | Single Language Context |
| **WEIRD** | Western Educated Industrialized Rich Democratic |

# 1 Introduction

## 1.1 Introduction

In a world characterised by increasing globalisation and interconnectedness, the phenomenon of bilingualism has gained prominence as a significant area of research into human communication and cognition. Bilingualism is the ability to proficiently use and understand two or more languages; this is a fairly complex and networked concept, encompassing a diverse array of linguistic and cognitive experiences, ranging from difference in language acquisition strategies (social vs. formal acquisition) to difference in usage patterns (individuals who effortlessly navigate between languages in their daily lives vs. people who use two languages in strictly different domains), includes bilinguals who may or may not be bicultural and so on.

Bilingualism, both social and individual, can arise through various pathways, including early exposure to multiple languages, migration, educational initiatives, and personal motivations. As a result, at the individual level, bilingualism manifests in different degrees of proficiency and language dominance across individuals. Before the cognitive aspects of bilingualism became a major focus of research, initial studies on bilingualism primarily focused on the linguistic, sociolinguistic, and even educational perspectives. The findings from these perspectives help lay the foundation for a deeper understanding of societal bilingualism and language use. One of the earliest and seminal works that had a major influence on subsequent bilingual studies is *Language in contact: Findings and problems*, a collection of essays by Uriel Weinreich (1953). He sheds light on the influence of one language of a bilingual speaker on their other language, terming this influence as 'interference'. This interference can be phonological, morphological, lexical and even grammatical in nature. He also mentions the various types of relationship that exists between the conceptual and lexical levels of representation, which laid the groundwork for what is today known as coordinate and compound bilinguals; coordinate bilinguals being those who learn their languages in separate environments, keeping them distinct and compound bilinguals being those who learn their languages in one environment, allowing more integration to take place among the languages. His theories on language contact and its social and structural effects paved the way for later studies involving language mixing, linguistic transfer, and bilingual speech processing.

Social bilingualism has been studied from several important perspectives for a long time. One of the foundational figures of sociolinguistics, Charles Ferguson, defined the phenomenon of diglossia (Ferguson, 1959), which describes a social scenario where two varieties of a language co-exist, with each variety having its clearly defined function, such as the High (or H) variety being used in formal settings such as education, administration, government, etc, and the Low (or L) variety which is used in more day-to-day conversations and settings. He was among the first to discuss language registers and how language varies according to the context, function, and audience. These concepts helped shape theories on code-switching and the social variation of language (1999). The works of Weinreich and Ferguson influenced other sociolinguists, such as Joshua Fishman. Fishman focused on bilingualism at a societal level, expanding on the concept of diglossia, stating that diglossia and bilingualism are not mutually exclusive and that societies can be bilingual without being diglossic and vice versa (1967). Fishman also introduced the concept of domains of language use (1965), which describes how bilinguals tend to use different languages in different settings, such as home, school, work, etc. Another key figure in the sociolinguistic research was John Gumperz. His contributions included a focus on interactional cues that extend beyond language, while also considering factors such as the intonation, tone, and context in a conversation. He also studied how bilinguals code-switch between their languages, stating that this code-switching was not random, but rather contextual, taking into account social cues (Gumperz, 1977).

Another domain of inquiry within bilingualism studies was language acquisition and bilingual education. Lambert extensively studied the French-English bilingual education in Canada and helped influence their educational policy. He challenged the idea that a bilingual is equally proficient in both their languages, calling it the balanced bilingual myth, stating that such a balance is quite rare, and how this would affect the cognitive development of a child (Peal & Lambert, 1962). Another key figure in bilingual language acquisition and the cognitive effects of bilingualism was Kenji Hakuta. He conducted one of the first longitudinal studies (Hakuta, 1976), documenting the second language acquisition of a Japanese-speaking child learning English. He detailed how second-language learners acquire their language over time, offering insights into interlanguage development. He further argues that bilingualism does not hinder intelligence or cognitive development (Hakuta, 1986), and that bilingual children develop metalinguistic awareness that can enhance their problem-solving skills.

By the late 20$^{th}$ century, the focus of bilingual studies had gradually shifted towards psycholinguistic and cognitive perspectives, examining the relationship between language and the brain. This shift was motivated by the realisation that bilingualism potentially affects language processing and brain function differently from monolingualism. One of the key figures in this regard was Ellen Bialystok, whose research provided a significant understanding of how bilingualism affects cognitive development, executive function, ageing, etc. Her early works focused on bilingual children, demonstrating their superior attentional control over monolinguals due to their constant management of their two linguistic systems (Bialystok, 1999). She further expanded on these findings, arguing that the bilingual experience enhanced one's executive control functions such as cognitive flexibility, inhibition, and task-switching (Bialystok, 2001; Bialystok et al., 2012; Bialystok, Kroll, et al., 2005; Bialystok, Martin, et al., 2005; Kroll & Bialystok, 2013). Her work also looked at ageing research and found that being bilingual might potentially delay cognitive decline and improve lifelong brain plasticity (Bialystok, Craik, et al., 2004; Bialystok et al., 2007, 2012; Bialystok, Martin, et al., 2005).

Beyond its linguistic implications, bilingualism has been shown to have a profound impact on cognitive processes, particularly executive control. Executive control, often referred to as executive functions or cognitive control, includes a set of higher-order cognitive functions that enable individuals to manage their thoughts, actions, and behaviours in a goal-directed manner. This complex set of abilities primarily includes skills such as inhibition, working memory, attentional control, and task-switching (Diamond, 2013; Lagattuta et al., 2015). Together they work towards a streamlined processing of a bilingual's language usage. The impact of speaking more than one language on one's cognitive abilities has been investigated by several researchers, taking into account each of those mentioned higher mental faculties. The initial results pointed to an advantage of bilinguals over monolinguals in terms of their performance in tasks involving those functions and this was termed the 'bilingual advantage' (Bialystok, Klein, et al., 2004; Hakuta & Diaz, 1985; Hilchey & Klein, 2011; Jiao et al., 2019; Yang & Yang, 2017); however, over time, the said advantage was questioned as more and more studies failed to replicate the findings (Dick et al., 2019; Lukasik et al., 2018; Paap et al., 2015; Paap & Greenberg, 2013; Shokrkon & Nicoladis, 2021; Timmermeister et al., 2020). This necessitated fine-tuning of the understanding of the cognitive underpinnings of speaking more than one language. Concepts like 'behavioural ecology of bilingualism' (Green, 2011) sought to explain the different results obtained from different groups of bilinguals. Similarly, researchers advocated taking socio-cultural factors into account while investigating this question, as language is primarily a social function (Gullifer & Titone, 2020). Linguistic behaviour of the bilingual group in terms of their language switching patterns is yet another framework that sought to connect bilingualism with cognitive abilities (J. Chen et al., 2023a; Gosselin & Sabourin, 2024; Hofweber et al., 2020; Jylkkä et al., 2021; Sanchez-Azanza et al., 2020; Yahya & Özkan, 2022). Last but not least, data from the Western Educated Industrialised Rich Democratic (WEIRD) nations, which formed the backbone of most of the predictions in the bilingual processing context, have been criticised (Henrich et al., 2010; Sanches de Oliveira & Bullock Oliveira, 2022) as the reason for the lack of generalizability of the results. The findings so far suggest that more work needs to be carried out from diverse parts of the world, encompassing different types of social realities and bilingual practices, to understand the finer workings of the human mind in this regard. At present, this seems to be the path forward, and Indian researchers can contribute to this ongoing debate, as India, like many other essentially bi/multilingual societies, has a rich tapestry of languages and cultures that coexist, and this complex structure has the potential to inform and impact human cognitive abilities.

Indian bilingualism has interested researchers since long. Initial studies looked at various sociolinguistic features of the same in terms of language contact and the creation of the Indian linguistic area (Emeneau, 1956; Ferguson, 1959; Ghatage, 1963; Pattanayak, 1990; Windmiller, 1954). Gradually, in recent years, empirical research into the psycholinguistic aspects of bilingualism has delved into the complexity of Indian bilingual language usage as well as the cognitive impact of bilingualism. These studies have looked at external factors that are socio-cultural in nature (Kechu et al., 2024), as well as internal factors, like proficiency (Dash & Kar, 2020), interaction with interlocutors (Bhandari et al., 2020; Rafeekh & Mishra, 2021), etc. While existing literature from India has explored some of these aspects, the current study takes those initiatives a step further by investigating the interaction between the external factor of a bilingual's interactional language usage and the internal factors of one's cognitive control mechanisms. Thereby, the current study aims to add a drop in the ocean of ever-expanding knowledge on human cognition through the lens of bilingualism. In order to do so, this work carried out experiments involving several executive control mechanisms on bilingual groups. The interrelationship between bilingualism and executive control mechanisms is tested here through the framework of the Adaptive Control Hypothesis (Green & Abutalebi, 2013).

## 1.2 Chapter overview

This chapter introduces the thesis, setting the scene for the research by looking at the work done so far and how it informs the research objective of this work. It first provides a short summary of the executive control mechanisms and their various components, along with a brief overview of the evolution of studies on bilingualism. This is followed by a brief survey of the Indian bilingualism research. Once the background is provided, the next section will examine the rationale behind the study and discuss the objectives that this study has put forward. The thesis structure is then briefly explained, followed by the conclusion to the chapter.

## 1.3 Human Cognition: Executive Control Mechanisms

Also known as executive function or cognitive control, this is a set of higher-order processes that help regulate one's thoughts and actions towards goal-oriented behaviour, involving problem-solving and decision-making in daily functioning and complex cognitive tasks (Miyake et al., 2000).

It consists of three core components: working memory, cognitive flexibility and inhibitory control. The components interact and facilitate higher-order functioning such as reasoning, planning and problem-solving. They develop gradually over the course of one's childhood, peak in early adulthood and then start to decline with age (Diamond, 2013; Miyake et al., 2000).

Over the past few decades, research on executive control functions has produced findings from branches of psychology, cognitive neuroscience, and even psycholinguistics, focusing on environmental factors that may influence this mechanism. A major trend of research has been the transferability of cognitive advantages. Studies have examined the transferability of cognitive advantages through various channels, such as video games (Gashaj et al., 2021; Peracchia et al., 2022; Strobach & Schubert, 2016), physical exercises (Bliss et al., 2021; R.-H. Li et al., 2024; Peracchia et al., 2022), mindfulness (Dong et al., 2023; Flook et al., 2024; Zhou et al., 2020), etc. Similarly, studies on bilingualism also suggest a bilingual advantage that stems from managing multiple languages, spilling over to non-linguistic cognitive functions. The scope of these advantages remains a source of debate and questions today, due to the mixed nature of the results obtained from the studies. Below, we discuss each of these components in some detail.

### 1.3.1 Working memory

The working memory is the system that provides temporary storage for information as well as the ability to hold, manipulate and update this information for complex functioning such as language comprehension, learning and reasoning (A. Baddeley, 1992). A key component that differentiates working memory from short-term memory is that while short-term memory is responsible for simply holding the information, working memory holds the information and further manipulates it (Diamond, 2013). Working memory performances have been shown to help predict performance in skills such as multitasking (Covre et al., 2019; S. Liu et al., 2016; Pollard & Courage, 2017), mathematical skills (Berkowitz et al., 2022; Pellizzoni et al., 2022; Simmons et al., 2012), media multitasking (Murphy & Creux, 2021; Uncapher et al., 2016), etc.

In 1974, Baddeley & Hitch introduced the multicomponent model of working memory, which explores how working memory relies on several cognitive mechanisms to function. This model was further expanded by Baddeley in 2000 (A. Baddeley, 2000), to include a fourth component. The four components included are: the phonological loop, which processes the verbal information, the visuospatial sketchpad, which manages the visual and spatial data; the central executive, which is responsible for cognitive flexibility and attentional control; and the episodic buffer, which integrates information from the previous three components and stores the information that is collectively processed by the other components.

In the past decade, studies have focused more on the impact that being bilingual has on the working memory, and considered it an integral component in bilingual cognition, where bilinguals are required to manage their different language systems, relying on the working memory to constantly update as per the changes in their linguistic environment (Bialystok et al., 2008). Being bilingual has shown a greater advantage when it comes to performance in working memory tasks (Jiao et al., 2019; Morrison et al., 2019; Yang & Yang, 2017). The findings, however, are mixed as several studies have also not reported any significant bilingual advantage in their working memory (Hartanto & Yang, 2016; Paap & Greenberg, 2013; Ratiu & Azuma, 2015).

### 1.3.2 Inhibitory control

Inhibitory control refers to the ability to suppress irrelevant distracting responses, thereby focusing on the goal-relevant stimuli. Without the inhibitory control in place, one would give in to their impulses, or pre-conditioned responses, not suited for the goal-oriented environment (Diamond, 2013). For instance, it is the inhibitory control that enables individuals to refrain from impulsively interrupting others in a conversation or snatch a toy from a child's hand. It primarily suppresses the irrelevant or competing information to maintain goal-directed behaviour. This theoretical framework is known as the inhibition theory (M. C. Anderson et al., 1994). It posits that the inhibitory control mechanism must constantly regulate the activation and suppression of information to prevent overload. The efficiency of this process is often mistakenly attributed to a single function, which is, rather, a composite of several functions working in tandem. This was further elaborated by Verbruggen & Logan (2017), who claimed that this process of response inhibition is an interaction largely between signal detection, action selection, and suppression of motor output, each of which is further broken down into smaller functions.

Inhibitory control has been widely studied in the context of typical and atypical cognition. Studies have also examined the relationship between inhibitory control and developmental disorders such as autism spectrum disorder (ASD), where participants with ASD showed delayed responses and reduced accuracy as compared to their neurotypical counterparts (Christ et al., 2007; Schmitt et al., 2018; Vara et al., 2014). They have also investigated the relationship between ageing and inhibitory control, specifically the effects of ageing on the mechanism, causing it to decline (Chao & Knight, 1997; Christ et al., 2001), with some studies saying that this decline could possibly be task-specific and not general (de Bruin & Sala, 2018). Research on inhibitory control in individuals with Alzheimer's disease has found that individuals with Alzheimer's have significant impairments in their response inhibition and interference control, owing to the cognitive decline that worsens as the disease progresses (Collette et al., 2009; Crawford et al., 2005; Martyr et al., 2019).

The last few decades have seen a growth in the research focusing on how inhibitory control interacts with language processing among the bilingual population performance (J. Chen et al., 2023a; Gosselin & Sabourin, 2023; S. Li et al., 2021; Madrazo & Bernardo, 2020; Yahya & Özkan, 2022). Several studies have suggested that the control exerted by bilinguals in inhibiting their non-target language has led to an enhancement of their inhibitory control mechanism. Since bilinguals frequently switch between languages, they need to inhibit the non-target language in order to produce fluent speech in the intended language. Green's (1998) The Inhibitory Control Model proposes that when a bilingual speaks in one language, the activation of the other language has to be actively suppressed. Neuroimaging studies showed that bilinguals exhibit increased activation in their prefrontal cortex and anterior cingulate cortex, both of which are areas associated with inhibitory control (D'Souza & D'Souza, 2016; Green & Abutalebi, 2013; Seo et al., 2018).

### 1.3.3 Cognitive flexibility

Cognitive flexibility refers to the ability to adapt to new information and respond accordingly, be it switching between tasks or adjusting cognitive strategies in response to changing environmental demands. In order to keep up with the changing demands of one's environment, one needs to inhibit previous actions (or thoughts) and update working memory with new information. Thus, this core cognitive process builds on the working memory and inhibitory control, and is considered to develop later than the other cognitive control functions (Diamond, 2013), and its decline due to ageing results in the inability to adapt to new situations and environments (Magnusson & Brim, 2014). It plays a crucial role in linguistic as well as non-linguistic mechanisms, such as problem-solving, multitasking, and adaptive behaviour. When performing a complex task, one has to constantly adapt to the environmental conditions. To do so, two things need to happen. One, they have to constantly focus their attention on the changing environmental conditions, and two, they need to constantly adapt their behaviour as per these aforementioned changes (Cañas, 2006).

This ability to maintain constant flexibility in response to changes in one's environment may be particularly relevant in the context of bilingual language usage, as bilinguals tend to frequently switch between languages based on conversational context and social cues. Gosselin & Sabourin (2024), for instance, found that a bilingual's code-switching abilities help train their cognitive flexibility, but only language-specific, and not domain-general cognitive flexibility.

While each component of executive control may operate independently for the most part, they often interact to perform more complex cognitive tasks. In bilinguals, such interactions are evident in language switching, where switching between languages involves suppression of one language and the activation of the other, requiring equal involvement of inhibitory control, working memory and cognitive flexibility.

### 1.3.4 Affective control

Affective control refers to the ability to regulate one's emotional responses to achieve goal-directed behaviour. It is considered to be another crucial component of the executive function, which allows people to manage emotional interference and maintain cognitive stability in environments that involve emotions (Schweizer et al., 2019). The interest in this field has been fairly recent, with several recent studies that have explored the interaction between affective control and executive control functions to see the impact emotion and its regulation might have on general cognitive functioning (Alguacil et al., 2013; Séguin et al., 2007; Tsermentseli & Poland, 2016).

Studies have investigated affective control in adolescents and found that they exhibit less developed affective control mechanism than adults, leading to increased impulsivity and heightened emotional reactivity, making them more prone to risk-taking and poor decision-making (Minihan et al., 2024; Schweizer et al., 2020; Steinberg, 2005). Affective control is also looked at while investigating affective disorders such as depression, as individuals with depressive symptoms tend to struggle with regulating negative emotions effectively. Studies have found that depressive patients tend to have difficulties inhibiting responses to negative stimuli and show an imbalance in emotional control (Fales et al., 2008; Joormann & Gotlib, 2010).

Bilingualism research over the years has explored the potential relationship between one's affective control and language usage. While interest in this interdisciplinary field is comparatively recent, the findings have been quite diverse. Studies have found that bilinguals show reduced emotional reaction when processing emotion words in their second language as compared to their first language, thus showing how language context influences emotion processing (Pavlenko, 2012). Alqarni & Dewaele (2020), for instance, found that bilinguals scored higher on their trait Emotional Intelligence than their monolingual counterparts. On the other hand, Dewaele (2021) found no relationship between emotional intelligence and knowledge of more languages.

## 1.4 Cognition and Bilingualism

The deep interconnectivity of language and cognition forms the foundation for human thought, communication, and interaction with the world around us. While language is often considered a channel for conveying meaning, its influence on cognition goes beyond communication, shaping how one perceives, categorises and processes information. Therefore, the study of language and cognition extends beyond linguistics, spanning multiple disciplines such as psycholinguistics, cognitive science, and neuroscience, among others, offering diverse perspectives on how language interacts with various cognitive processes, including inhibition, working memory, emotion, and attention.

Similarly, over the past century, research on bilingualism has significantly evolved, with the increasing involvement of psychological, cognitive science, and neuroscience perspectives. Studies on bilingualism in the early 20th century suggested that bilingual children suffered from intellectual disadvantages, lower IQ scores, and language confusion. Saer in 1923, for instance, looked at the intelligence levels of English monolinguals and Welsh-English bilingual children by administering verbal intelligence tests. Results showed that bilingual children showed significantly lower IQ than their monolingual counterparts. He then concluded that bilingualism obstructed intellectual development, due to the added cognitive load that came from handling two languages. However, a later review of such studies from that time revealed various methodological flaws, such as language bias in IQ tests and a failure to control for external factors, including socioeconomic status, educational background, etc. In 1962, the landmark study by Peal & Lambert found that bilingual children outperformed their monolingual peers in various cognitive tasks, thereby changing the negative perspective on bilingualism, instead viewing it as a cognitive asset.

Research on bilingualism from this time onward focused on factors such as executive functions, metalinguistic awareness, and the role of bilingual experience in shaping one's cognitive faculties. The enhanced cognitive abilities often observed in individuals who navigate multiple linguistic systems were termed 'bilingual advantage'. This bilingual advantage has been a source of intense debate in the past decade or so, with studies over the years showing vastly varying results on the presence of this phenomenon in bilingual speakers (Chung-Fat-Yim et al., 2019; Esposito et al., 2013; Foy & Mann, 2014; Gade et al., 2024; Jiao et al., 2019; Khodos et al., 2021; Sanchez-Azanza et al., 2020). Many studies failed to replicate the 'advantage', thereby pointing to the possibility that it is not bilingualism per se, but the 'type' of bilingualism practised by the different bilingual groups that results in the said advantage, or it does not (Jylkkä et al., 2017, 2018; Kałamała, Szewczyk, et al., 2020; Paap et al., 2021; Yang et al., 2023). As a result, multiple new variables have become integral to bilingualism research, often leading to the development of new theories to understand the phenomenon. We discuss them below.

### 1.4.1 Language Switching and its cognitive implications

A key component that comes with being bilingual is the ability to decide which of the languages a bilingual must use in a situation. Earlier studies on bilingualism largely focused on its social and linguistic aspects. For instance, J. Fishman, in 1965, introduced the framework of domains of language use, which posits that bilinguals do not randomly switch languages but do so depending on the context and social setting. The increasing interest in the field of cognitive science led to this phenomenon being examined for its processing demands and the involvement of cognitive mechanisms. The seminal study by Macnamara & Kushnir in 1971 was among the first papers to investigate the reaction time costs associated with switching between languages. Results showed that participants had slower reaction times when they switched from one language to another, suggesting the presence of additional cognitive load during language switching. Dalrymple-Alford (1985) investigated the reaction time performance of participants while switching languages in a verbal task and found that when switching to the dominant language, reaction time tends to increase, suggesting that cognitive effort might be needed to inhibit the language when not in use. Soares & Grosjean (1984) further found that language switching required involvement of the executive control mechanism, and that switching between languages came with processing delays.

This past decade has seen a revolution in bilingual studies, moving towards a more nuanced view, placing more emphasis on variability in bilingual experiences and how it shapes cognition. This has led to a shift in the perspective that all bilingual experience is universal and instead considers it to be a sum of the many factors that make a bilingual. In her paper, Bialystok (2021) compares the bilingual experience to a pack of Swiss cheese, with its holes being compared to the different manifestations of bilingualism that collectively make up this block of cheese, so to speak. She further states:

*"Anticipating where those holes are for bilingualism is especially challenging because each experience of bilingualism is different. Although such differences as age of acquisition of the additional language(s), duration of active bilingualism, intensity of use, proficiency in each language, and the like (…), have been acknowledged for some time, detailed examination of them has only recently become an important area of research."* (p. 3)

This shift led to the rise of several theories and models that look at how bilinguals manage their languages, how the executive control mechanisms operate in bilingual contexts and how one's linguistic environment shapes their language use. This section will explore some of the key theoretical frameworks that have helped influence and shape contemporary bilingualism research.

#### 1.4.1.1 Inhibitory Control Model

Proposed by Green in 1998, it explained how bilinguals managed two language systems using domain-general inhibitory control mechanisms through multiple levels of control. According to this model, when a bilingual selects a language to communicate in, the lexical representations of both their languages get activated. Using the inhibitory control mechanism, the non-target language gets suppressed, allowing fluent speech in the target language. The inhibition is asymmetric, with the bilingual's dominant language requiring greater suppression than their weaker language. The constant suppression of the non-target language would give the bilinguals enhanced inhibitory control.

Green's Inhibitory Control Model has had a significant impact on bilingualism research that focused on language switching and executive control functions. It highlights the cognitive demands of bilingualism, connecting language control with general cognitive functions such as inhibitory control. It paved the way for later models such as the Adaptive Control Hypothesis, which better defined the role of executive control functions in a bilingual's linguistic environment.

### 1.4.1.2 Language mode continuum

This framework, proposed by François Grosjean (1985, 1994, 1997, 1998, 2013), explains how bilinguals navigate between their languages depending on the contextual demands. According to this model, a bilingual's languages operate along a continuum of activation, ranging from monolingual mode, where only one language is activated while the other is inhibited, to completely bilingual mode, where both languages are active and used interchangeably.

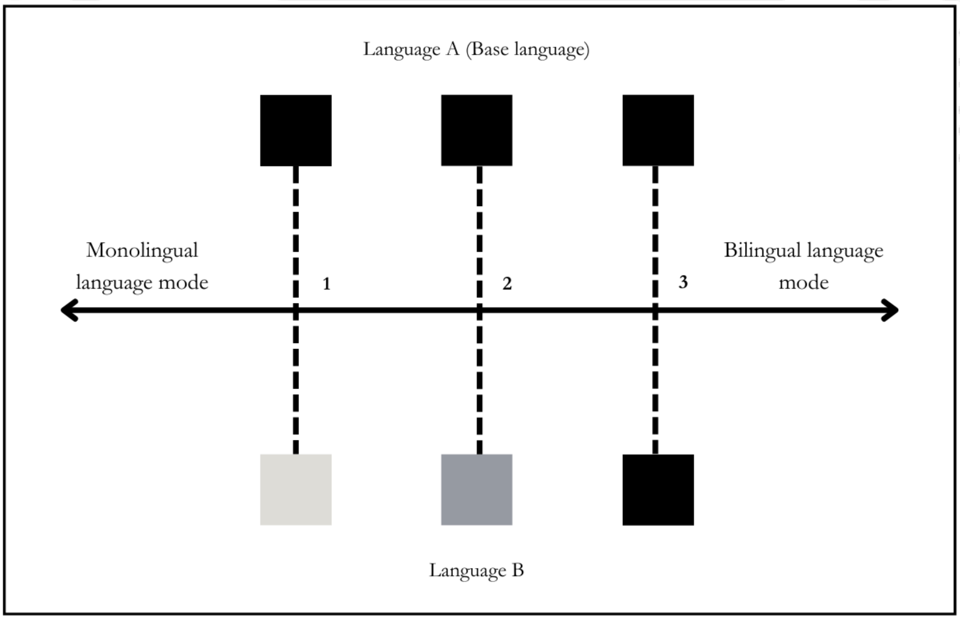


*Figure 1.4.1: Language mode continuum flowchart. (Adapted from Grosjean (2013))*

Figure 1.4.1 shows the flowchart of the language mode continuum. In monolingual mode, a bilingual tends to suppress one language as much as possible to communicate like a monolingual speaker. This takes place in an environment with monolingual individuals, where only one language is used. In bilingual mode, on the other hand, both languages are active, with possible code-switching and mixing, mostly in conversations with other bilinguals. In the figure, the black square represents active language and levels of activation of language B are represented by the degree of darkness of the square- darker the square, greater the activation. The degree of activation of the languages is determined by factors that may be external (such as the participants in the conversation, its setting, etc.) as well as internal (involvement of executive control mechanisms such as working memory and inhibitory control) in nature.

Grosjean's model challenged the notion prevalent at the time of bilinguals functioning as two monolinguals and instead emphasised on the dynamic and fluid nature of bilingual language processing. It was crucial in getting a better understanding of the nature of language switching, as well as the mechanisms involved in bilingual cognition

### 1.4.1.3 Adaptive Control Hypothesis

One of the prominent theories that accounts for the finer aspects of bilingual advantage (or lack thereof) is the Adaptive Control Hypothesis (henceforth referred to as ACH) (Green & Abutalebi, 2013), according to which, the executive control adapts itself to the demands it is put under. A bilingual's languages remain in a constantly activated state, even if they are currently not using all the languages in their repertoire, meaning that the cognitive control is in a state of activation higher than that of monolinguals. However, this state of activation varies depending on the interactional context of the bilingual speaker. Figure 1.4.2 depicts the architecture of the Adaptive Control Hypothesis. The interactional context determines what and how a bilingual would use their languages. The processing of the language follows a speech pipeline, which includes several stages, such as conceptual (thoughts), affective (emotions), linguistic (words and grammar selection), and the sensorimotor (involving production of speech), all of which have to be managed effectively. The control processes involved, like the working memory, regulate these stages and ensure effective communication, while the higher-order meta-control processes adjust the control exerted, depending upon the contextual situation. Over time, the brain adapts to the processing through structural changes like changes in grey-matter density, improved efficiency in brain regions that can be seen through fine-tuned neuronal activity, and enhanced connectivity between brain regions visible through stronger white-matter connections.

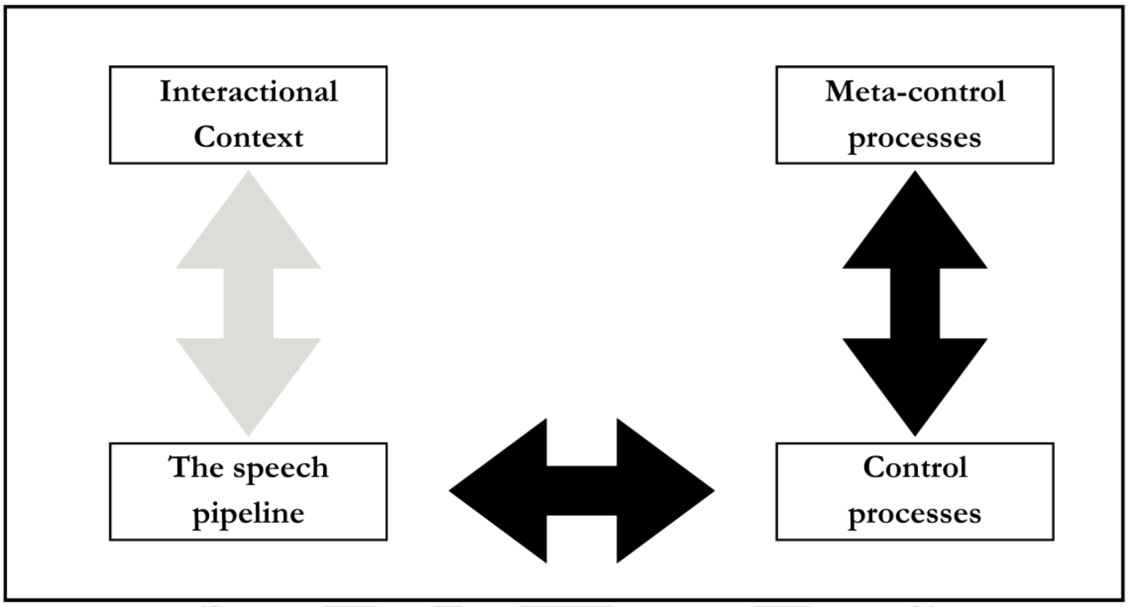


*Figure 1.4.2: Architecture of the Adaptive Control Hypothesis. The darker arrows depict internal processes of control. (Adapted from Green & Abutalebi (2013)).*

The hypothesis proposes three broad contextual (language usage) scenarios and the varying levels of cognitive control exerted by each of them. First is the *Single-Language Context*, in this context, the speaker has distinct languages for separate linguistic environments, with little to no switching between the speaker's languages. For instance, using English (second language: L2) in formal work settings and one's first language (L1) at home. Each language has its specific function, and very little (if any) code-switching takes place. The second context is the *Dual-Language Context*, where, within a linguistic environment, the participants switch between languages as per the changing context. For instance, if two bilinguals are speaking Language 1, and a third participant joins in, who is not familiar with Language 1, the participants switch to another language that is mutually understood among all speakers. In this scenario, code-mixing is more apparent, with participants changing between languages as per the dynamic shifts in the environment. Finally, there is the *Dense Code-Switching Context*, where context-free language switching takes place. The participants in this context freely switch between their languages within an utterance, with the occurrence of frequent code-switching. As per the ACH, the demands of constant vigilance on the target languages in Dual-Language Context translate to having a greater exertion on general executive control functions, leading to enhanced mechanisms of control. Thus, the ACH suggests that bilinguals tend to adapt their cognitive control systems based on their language environment, which further influences their general cognitive control systems.

The abovementioned three language usage contexts include most forms of general everyday language usage among bilinguals. The framework of language usage is seen to be in a competitive relationship in single and dual language contexts, but in a cooperative relationship in dense code-switching context. This relationship is what determines the extent of participation of the control processes that are involved in language usage, which then spills over onto cognitive processes not involved in linguistic functions. In their paper, they have specified 8 control processes that are said to have been involved in language usage context, and the extent of their involvement *(see Table 1.4.1)*. Below, we will discuss each of these control processes in detail.

| Control Process | Single language | Dual language | Dense code-switching |
|---|---|---|---|
| **Goal Maintenance** | + | + | = |
| **Conflict Monitoring** | + | + | = |
| **Interference Suppression** | + | + | = |
| **Salient Cue Detection** | = | + | = |
| **Selective Response Inhibition** | = | + | = |
| **Task Disengagement** | = | + | = |
| **Task Engagement** | = | + | = |
| **Opportunistic Planning** | = | = | + |

*Table 1.4.1: Cognitive control processes and interactive contexts. (+) means the control process is involved in that interactional context & (=) means it is unlikely to be affected by it, as compared to a monolingual speaker in a monolingual setting. (Green & Abutalebi. 2013).*

### *Goal Maintenance*

This includes processes that are involved in actively looking out for external and internal cues, and producing responses as per what the situation demands, to maintain the representations of the demands of the task at hand, till the task is concluded. In the case of language usage context, this cognitive process would be used in Single-Language as well as Dual-Language contexts, where the speaker must maintain the goal of speaking in one language and not switch to the other. This would be in higher demand in the Dual-Language Context speakers, whose environment would be more dynamic, and therefore they would need to maintain the language or switch, often within the same conversation.

Some studies have broken down the function of goal maintenance as a combined effort of two executive functions: one involved in proactive control, the control involved in monitoring and two, the control involved in reactive control (Mäki-Marttunen et al., 2019; Morales et al., 2013). The executive functions said to be involved in this process would include the working memory and inhibitory control, where the working memory would need to update itself to the changes in the cues provided, and the inhibitory control would need to suppress the language not being used at the time. The goal needs to be clearly maintained for the executive control to know what is relevant to the task at hand and what needs to be inhibited, leading to the working memory and the inhibitory control working in tandem.

The tasks often used for investigating goal maintenance are AX-CPT (Continuous Performance Task) (Lopez-Garcia et al., 2016; Mäki-Marttunen et al., 2019; Morales et al., 2013) as well as task switching tasks (Chan et al., 2020; Declerck et al., 2017; Mas-Herrero et al., 2021). On breaking down the processes involved, the *N*-Back task (Morrison et al., 2019) or Antisaccade (Kałamała, Szewczyk, et al., 2020) are popular tasks for measuring working memory, whereas for inhibition, tasks such as Simon Task (Tse & Altarriba, 2014), Flanker Task (Antón et al., 2019; Jiao et al., 2019), Go/No-go Task (Jiao et al., 2019), Stroop Task (Antón et al., 2019; Tse & Altarriba, 2012) are often used.

Tse & Altarriba (2012) tested the effect of bilinguals' proficiency of their L1 and L2 on the function of goal maintenance, keeping in focus their performance with respect to their selective attention. The participants performed the Stroop task, and it was found that their proficiency in their L1 and L2 had an effect on their performance in the task.

Morales et al. (2013) compared the performances of monolinguals and bilinguals in the AX version of CPT to compare their performances in executive functions combining monitoring and inhibition processes, and found that the bilinguals outperformed the monolinguals in the task.

Thus, goal maintenance is an important process of the executive control which combines the processes of inhibition and working memory. As per the Adaptive Control Hypothesis, while it is active in both Single-Language and Dual-Language context groups, it would be more prevalent in Dual-Language context speakers. To further aid the process of maintaining the goal of speaking the current language and not being distracted by the external cues being present, the cognitive process of interference control comes into play.

### *Interference Control: Conflict Monitoring and Interference Suppression*

The process of interference control is made up of two top-down processes of conflict monitoring and interference suppression. These two processes fall under the umbrella of the core executive control function of inhibitory control.

Conflict monitoring comes in when simultaneous cues in one's surroundings place demands on one's cognitive control. According to the conflict monitoring theory (Botvinick et al., 2001), when multiple conflicting cues are present in the environment, it brings about an increase in the allotment of cognitive processes towards the task at hand and away from the distracting cues. This function recruits the processes of inhibitory control to suppress engagement in distractor cues and the working memory to update new task demands at hand.

Costa et al. (2009) examined the presence of any advantage that bilinguals might have in conflict monitoring over monolinguals. The participants were made to perform the Flanker task with varying levels of monitoring required. They found that while in a low monitoring task, the performances of the monolinguals and bilinguals were more or less at par with each other, whereas in the task that needed high monitoring, the bilinguals outperformed the monolinguals.

The process of conflict monitoring is almost immediately followed by the process of Interference suppression. This process takes care of the distracting stimuli by suppressing attention, and subsequently other cognitive resources towards it. Some tasks that focus on interference suppression include Stroop and Flanker (Brydges et al., 2013; Dignath et al., 2020), where irrelevant information must be suppressed to respond to the relevant cues. In the case of Stroop task, suppressing the response to the written words and instead focusing on their colour. Or, in the case of Flanker task, to ignore the cues surrounding the central cue and focus on responding only to the direction of the central cue.

According to the ACH, the combined processes of conflict monitoring and interference suppression act to suppress distracting cues such as voices of other speakers not relevant to the conversation, which might activate the goal of switching to another language. In Single-Language Context, while this process of interference control is present, it is however, not as taxed as in Dual-Language Context. This is because in Single-Language Context, there is an exclusivity for the usage of the languages of a bilingual, with little to no chance of overlap between the various languages. On the other hand, for Dual-Language Context speakers, switching among languages is prevalent within an environment, thus placing a greater strain on the interference control function.

***Selective Response Inhibition***

Recent studies (Xie et al., 2017) have suggested that the inhibitory control may comprise multiple functions combined instead of one main function. Two of the functions included in this are interference control and response inhibition. Selective response inhibition is another cognitive control process that is also included among the 8 control processes in the ACH, and is the ability to subdue a response that is either dominant or ongoing (Kałamała, Szewczyk, et al., 2020) in favour of a more task-relevant response. It is suppressing a response which may not be relevant to the task at hand or which may interfere with goal-directed behaviour. While this can be viewed as an extension of interference suppression, however, interference suppression happens while continuing the task at hand, whereas selective response inhibition comes into play when the goal of the task to be performed changes and a new task goal gets updated, leading to a need for unwanted responses to be inhibited.

According to the ACH, the function of selective response inhibition includes inhibiting an ongoing response to make way for a more goal-relevant behaviour. In the case of bilinguals, this particular cognitive process will be most taxed among the Dual-Language context group as compared to the Single-Language and Dense code-switching context groups. In fact, in the Single-Language and Dense code-switching context groups, this control process will be neutral in this effect. In the case of Single-Language context, the environments for the languages of the bilingual are well-defined and there is very little to no overlap between these interactional contexts. Thus, no language switching takes place, and the involvement of the cognitive process of selective response inhibition is minimal. Similarly, in the case of Dense code-switching context, since there is regular mixing of languages taking place, even within the span of a single utterance, the selective response inhibition function has little else to do in this particular context. However, when it comes to the Dual-Language Context, switching may not occur within the same utterance, but the same speaker may change languages depending on the person they are interacting with. Therefore, in this interactional context, there is an increase in the demand on the control process of selective response inhibition.

Common tests to measure selective response inhibition include the Antisaccade task (Kałamała, Szewczyk, et al., 2020), Go/No-go task, Stop-signal task (Gillespie et al., 2022; Kałamała, Szewczyk, et al., 2020), and the Stroop task (Kałamała, Szewczyk, et al., 2020). Stroop and Go/No-go have also been suggested by Green & Abutalebi (2013) as measures to investigate this cognitive process. For instance, in the Go/No-go task, the participant has to respond to one of the stimuli and refrain from responding to the other stimulus. The control process of selective response inhibition comes into play when switching between these two opposing responses to the stimuli. Similarly, in the classic Stroop task, the participant is supposed to respond to the colour of the text and ignore the text itself. Here, the function of the selective response inhibition is to inhibit responding to the written text and instead focus on the task of responding to the colour of the text.

#### *Salient cue detection*

The function of salient cue detection is to keep a watch for prompts in one's environment and update one's task schema according to the cues they receive. In tasks such as a bivalent task switching task, the cue prompt would determine which task is to be performed by the participant. Green & Abutalebi (2013) in their paper on the Adaptive Control Hypothesis recommended the Go/No-go task to test the function of salient cue detection.

According to the ACH, this function is more prevalent in the Dual-Language Context, whereas in Single-Language and Dense code-switching contexts, this function remains neutral. In the Dual Language Context, the speaker has to be aware of their environment, for instance, if a new participant enters the conversation, which may require the speaker to update their task schema and either continue with the language they were speaking in, or depending on the preference of the new participant, change the language to one that all participants are comfortable in.

***Task Disengagement and Task Engagement***

This combined set of processes is involved when shifting focus from one activity to the other. It includes first identifying that the task schema needs updating, then withdrawing from the current task at hand, followed by shifting to a new task.

As per the ACH, it is a continuation of the process after selective response inhibition. It starts with first discontinuing from speaking the language the speaker is currently speaking in, i.e., disengaging from a task, followed by switching to a new language to speak, in other words, engaging in a new task. These processes collectively also involve the processes of conflict monitoring and interference suppression, because the current task schema needs to be suppressed and a new task has to be activated. Single-Language Context and Dense code-switching Context are both neutral when it comes to the cognitive processes of task disengagement and engagement. On the other hand, in the context of Dual-Language, the speaker has to constantly be aware of their environment and keep track of the possibility of a new speaker into the conversation, wherein they may need to disengage from the language they are currently speaking and engage in the new language as per the requirement of the context. One effective way to examine these cognitive control processes is to use the task-switching tasks.

***Opportunistic Planning***

The final cognitive control process mentioned is Opportunistic planning. Hayes-Roth & Hayes-Roth (1979), described this process as a more spontaneous manner of taking advantage of the changes in one's environment and using it to continue to achieve one's goals. This approach of achieving one's goals was considered different from the more conventional and systematic top-down approach in the manner in which it tackled its task goals. It allowed the planner not to worry about maintaining the rigidity of the premeditated decision made. Rather, opportunistic planning kept the task goals in mind and with partial plans made, the emphasis was more on achieving the goals as the opportunities arose. Thus, it involves fetching the goal from memory at some point, possibly in the future, when the environment is perceived to be conducive to satisfying the said goal (Patalano & Seifert, 1997).

Within the framework of the Adaptive Control Hypothesis, opportunistic planning in a bilingual speaker would, for instance, take place when the speaker tries to fit words of one of their language within the syntactic structure of another of their language, in an attempt to mix their languages within an utterance. The Dense code-switching context is said to require this cognitive control process more than the Single and Dual language contexts, due to the nature of constant language switching that takes place.

Since it first came out, several studies have investigated the implications of ACH, but with mixed results. Some results corroborate the predictions of ACH, while some do not, and yet others do so, partially. Some studies have included participants with varying linguistic experience, be it participants in a WEIRD environment (Gosselin & Sabourin, 2023; Kałamała, Szewczyk, et al., 2020; Nour et al., 2020), non-WEIRD environment (X. Han et al., 2023; Rafeekh & Mishra, 2021; Yang et al., 2023), WEIRD sample vs. non-WEIRD sample (Ooi et al., 2018), and even non-WEIRD participants in a WEIRD environment (X. Han et al., 2022, 2024). Results have shown that the environment of the participants may not be a reliable predictor. Some studies corroborated the hypothesis (Gosselin & Sabourin, 2023; X. Han et al., 2023), some did not (Kałamała, Szewczyk, et al., 2020; Yang et al., 2023), and others showed partial fulfilment (X. Han et al., 2022, 2024; Nour et al., 2020; Ooi et al., 2018; Rafeekh & Mishra, 2021), regardless of their linguistic environment.

#### 1.4.1.4 Language Entropy

Proposed by Gullifer & Titone in 2020, this framework is a more recent approach to bilingualism research that builds off the Adaptive Control Hypothesis. It offers a more quantitative approach to measuring the bilingual experience by capturing the variability of language use across different contexts. This approach further steered away from traditional bilingualism research of categorising bilinguals based on static measures that failed to completely account for the dynamic and context-dependent nature of bilingual language use.

Derived from information theory, this concept provides a mathematical measure of linguistic diversity to help examine a bilingual's language usage in real-life scenarios. Entropy refers to uncertainty, and when applied to bilingualism, it helps measure the degree of dominance in an individual's language across various contexts. For instance, if a bilingual consistently uses one language across several domains such as home, work, social settings, etc., then their language entropy is considered low, indicating a predictable and structured linguistic environment. On the other hand, if the bilingual speaker frequently switches between their languages in different domains, their language entropy is high, indicating a more dynamic and unpredictable linguistic environment. In order to quantify this entropy, participants reported their language use across different contexts, and using a statistical approach, the indices of language use across various domains were developed using self-reported language usage. A formula is used to calculate the entropy, with higher values representing greater linguistic diversity.

The language entropy framework marks a significant shift in bilingualism research, beyond static labels, to a more dynamic, context-sensitive approach, providing a more nuanced approach to studying individual differences in bilinguals and their impact on cognitive mechanisms.

## 1.5 Bilingualism in the Indian context

One of the most linguistically diverse countries in the world, India has a rich, complex and multilingual landscape shaped by historical, cultural and socio-political factors. While the Linguistic Survey of India lists a total of 179 languages, including 544 dialects, as per the 2011 Census data, India has approximately 120 languages, with 19,500 dialects and recognises 22 major languages as scheduled languages (Census of India, 2011. (Office of the Registrar General & Census Commissioner, India. Ministry of Home Affairs, Government of India), *[https://censusindia.gov.in/nada/index.php/catalog/42458/download/46089/C-16_25062018.pdf]*, retrieved on 19th February, 2025). These languages belong to various language families, primarily 4 major language families, namely:

- Indo-European, more appropriately, its sub-branch, the Indo-Aryan language family. It comprises 78.07% of the total Indian population. 23 languages in India fall under this sub-branch, including Assamese, Dogri, Hindi, Kashmiri, Maithili, Odia, Sanskrit, Urdu, etc. *(see Figure 1.5.1(A))*.
- Dravidian language family, which consists of 19.64% of the total population. Around 17 languages come under this sub-group. This includes Kannada, Malayalam, Parji, Tamil, Telugu, etc. *(see Figure 1.5.1(B))*.
- Austro-Asiatic language family, which is made up of 1.11% of the total population. It includes 14 Indian languages such as Kharin, Khasi, Munda, Nicobarese, Sanatali, etc. *(see Figure 1.5.1(C))*.
- Tibeto-Burman language family, which is a sub-branch of the Tibeto-Burman language family that comprises 1.01% of the total Indian population. 66 Indian languages are a part of this language family, including Angami, Bodo, Chakhesang, Garo, Hmar, Karbi, Lepcha, Mizo, Nocte, Paite, Sema, Tangkhul, and Zou *(see Figure 1.5.1(D))*.

Today, factors such as inter-regional migration due to education, work and better prospects have caused a rise in societal bilingualism, especially among the younger population. This has led to people having the knowledge and usage of more languages, apart from their mother tongue. As per the 2011 census data, the national rate of bilingualism in the country increased from 4.79% in the 2001 census to 26.01% in the 2011 census. The national rate of trilingualism, according to the 2011 census data, was 7.10%. (Language Atlas. (Language Division. Office of the Registrar General & Census Commissioner, India. Ministry of Home Affairs, Government of India) *[https://language.census.gov.in/eLanguageDivision_VirtualPath/Atlas/pdf/2011.pdf]*, retrieved on 20th February, 2025).

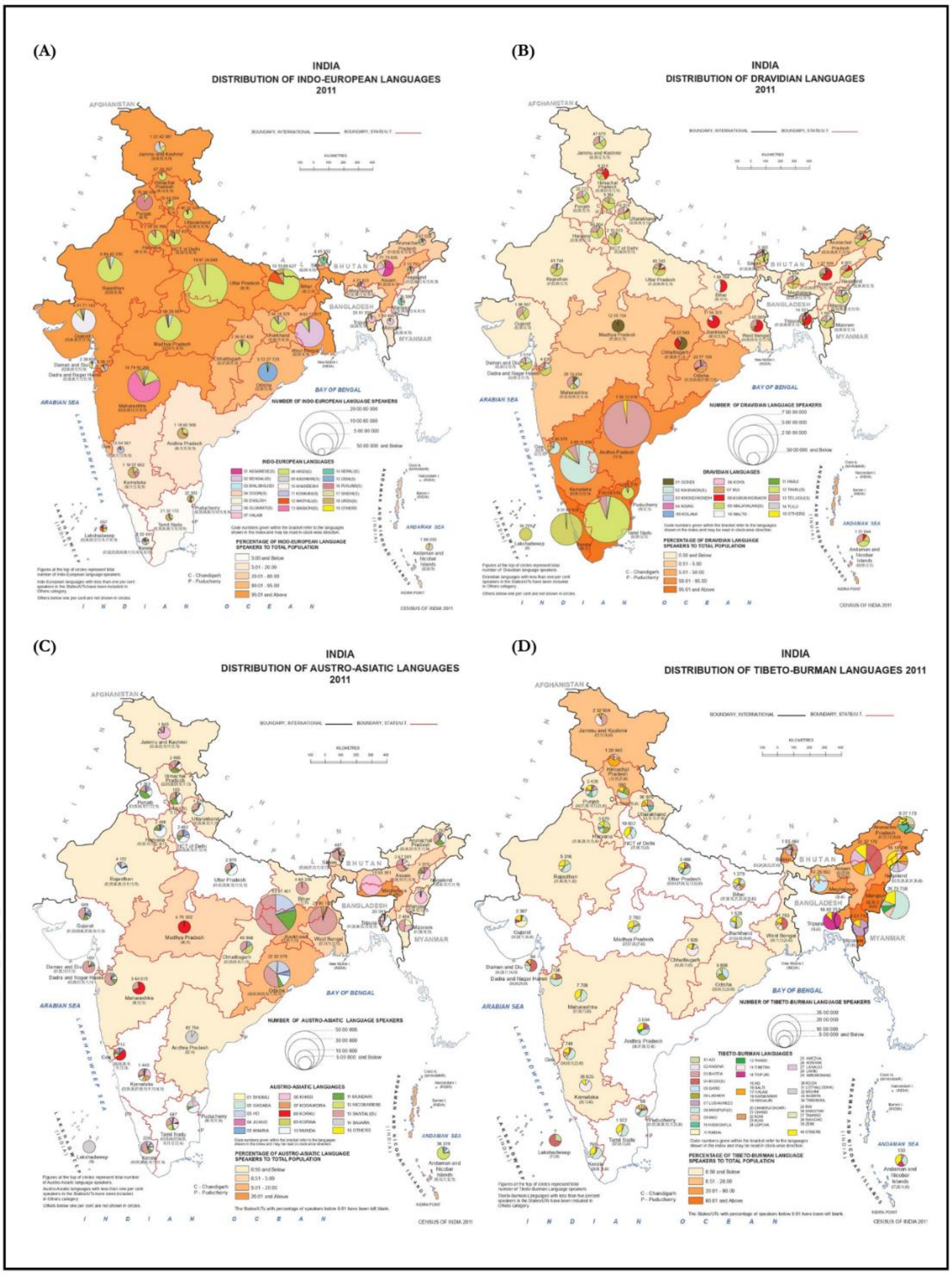


*Figure 1.5.1: Indian maps as per the distribution of the language families. (Clockwise: (A) Indo-European languages, (B) Dravidian languages, (C) Austro-Asiatic languages, and (D) Tibeto-Burman languages. Source: Language Atlas. (Language Division. Office of the Registrar General & Census Commissioner, India. Ministry of Home Affairs, Government of India) [https://language.census.gov.in/eLanguageDivision_VirtualPath/Atlas/pdf/2011.pdf], retrieved on 20th February, 2025).*

Bilingualism in India is shaped by several factors, such as colonial encounters, linguistic diversity, socio-political transformations, etc. It is not a novel phenomenon and can be traced back to the pre-colonial period, and can be traced back through its cultural, religious and administrative history. The linguistic diversity of this subcontinent was shaped by centuries of migration, political expansions, and religious practices, which fostered a natural environment for bilingual and multilingual communication.

In his seminal paper 'India as a Linguistic Area', Murray B. Emeneau (1956) stated that while the languages spoken in India all belonged to various language families, they all shared certain linguistic traits such as retroflex sounds, word order, preferential use of suffixes over prefixes and infixes, use of postpositions, morphological reduplication, etc (Emeneau, 1956; Kulkarni-Joshi, 2019). Similarly, the presence of Dravidian words in Sanskrit, which at the time was predominantly spoken mostly in the Northern parts of India, also alludes to the fact that the Dravidian language was localised there at some point. He states that these shared traits and borrowings are not due to genetic factors, but rather a result of language contact and bilingualism. Franciscus Kuiper's 'The Genesis of a Linguistic Area' (1967) further builds on Emeneau's concept of India as a linguistic area. He also agrees with Emeneau's theory that the shared linguistic features of the Indian languages come from prolonged language contact and bilingualism, which further give rise to linguistic areas. Kuiper also states that continuous and widespread bilingualism lead to the gradual adoption of linguistic traits across the Indian languages, which potentially lead to language convergence. Gumperz (1977, 1982) in his work examining North-Indian youths also contributed to this discourse with his work on conversational code-switching, which is a practice of switching between languages in a conversation, commonly seen among bilinguals. He stated that code-switching was not random but rather a reflection of the interpersonal relationships among the participants of the conversation, and that speakers switched between languages for status, emotional emphasis, etc.

The British colonial period played a significant role in shaping bilingualism in India with the introduction of English. This was further seen when India's language policy introduced the three-language formula in 1968 in order to promote multilingualism. The three languages included study of a modern Indian language, along with Hindi and English in Hindi-speaking states, and regional language, Hindi and English in non-Hindi-speaking states (Ministry of Education, Government of India. *[https://www.education.gov.in/sites/upload_files/mhrd/files/document-reports/NPE-1968.pdf]* retrieved on 7th March, 2025), in order to promote balanced bilingualism in the country.

In his work, Indian sociolinguist Braj B. Kacharu (1985) expanded on the concept of World Englishes, which stated that the traditional idea of American and British English should not be considered as the only standard versions of English and that indigenized versions of English spoken in post-colonised communities should be recognised as varieties of the English language as well. He introduced the concept of the Three Circles of English, which classifies the spread of English in three concentric circles. The first circle is the Inner Circle, which includes native English-speaking countries such as the UK and the USA. The second circle is the Outer Circle, which includes countries like Malaysia, Singapore, India, etc. The third circle is the Expanding

Circle, which includes countries where English is used as a foreign language, in education, with countries like Turkey, Japan, Korea, etc. This helped understand how English had become an essential part of Indian identity in the postcolonial era. It was associated with socioeconomic mobility, leading to an increasing preference for English-medium education. Following Kachru's work on World Englishes, sociolinguistics research expanded in several directions. These trends included social and functional roles of Indian English (Mehrotra, 1998; Ramanathan, 2005; S. Singh & Kumar, 2014), multilingualism and language policy in India (Annamalai, 2001; Pattanayak, 1990; Saraf, 2014), etc.

Research on bilingualism and its cognitive effects, in the Indian context, has produced interesting results over the past decade. While previous studies on Indian languages focused more on their linguistic features, historicity, and social impacts, work on the cognitive outcomes of Indian bilingualism is still in its nascent stage. There are several studies that have examined the cognitive effects of being bilingual by examining participants from different language families, such as Hindi-English bilinguals (Dash & Kar, 2020; J. P. Singh et al., 2019; Thanissery et al., 2020), Telugu-English bilinguals (Bhandari et al., 2020; Mishra et al., 2019), Malayalam-English (Rafeekh & Mishra, 2021), etc. These studies have focused on different aspects of bilingualism, such as proficiency, interlocutor interaction, sociolinguistic factors and so on. However, these studies have not looked at language switching as a variable in the executive control mechanism exhibited by bilinguals. Also, in most cases, the bilinguals who participated in these studies have English as their second language, thus not considering the scenario where the bilinguals use two or more Indian languages in their repertoire.

## 1.6 Rationale of the present study

While studies on cognition in the Indian bilingual population have examined bilinguals from specific language communities, they have not considered the language switching and interaction among different languages/communities that take place on a regular basis. Similarly, the mixed results among the young adult bilingual population obtained by previous studies examining the interaction between bilingual advantage and language-switching context point to the necessity to investigate this issue in as many and varied groups as possible.

Therefore, the current study attempts to examine a slice of population-behaviour that is representative of the young generation, who speak several languages, easily mingle in a diverse set of cultural setups and have a general 'pan Indian' identity (while not compromising their own individual cultural connections/roots), and not focus on a specific bilingual language community. The study can be said to represent a particular age group of Indians, with shared characteristics. The young generation today is more alike than ever before, largely due to increased social mobility and the widespread use of the internet.

India is a rich storehouse of different types of bilingualism practised at various levels, and being bilingual here is considered a norm, not a novelty. Studying Indian bilingualism through the premises of the Adaptive Control Hypothesis (also referred to as ACH) can thus shed light on the nuances within bilingualism. This way, the study may contribute evidence from a non-WEIRD (Western, Educated, Industrialised, Rich, Democratic) country to the ongoing debate.

## 1.7 Research aim, Questions and Hypothesis

### 1.7.1 Aim

The aim of this thesis is to investigate the relationship between contextual language usage and performance in higher-order skills, such as the executive control function, among the young adult population from different language communities in the Indian bilingual context. The core executive control functions, namely working memory, switching and flexibility, and inhibitory control, are investigated through various behavioural tasks, such as univalent and bivalent switching tasks, *N*-Back task, Simon task, Stroop task, Go/No-go task, etc.

### 1.7.2 Research questions

The specific research questions asked are as follows:

1. Would contextual language switching habits affect the performance in task switching?
2. Would contextual language usage have any effect on the performance of working memory function?
3. What would be the effect of contextual language usage on the inhibitory control function?
4. Would interactional language usage have any influence on the performance of the affective control function?

### 1.7.3 Hypothesis

Given the premise of the ACH, we expect that a higher complexity of interactional language usage, exhibited by bilingual speakers, will lead to better performance in the executive control functions. In other words, bilingual speakers engaged in Dual-Language context usage will show better performance than other bilingual speakers across various executive control functions.

The hypothesis is articulated as follows: The more complex the language switching context, the better the performance in tasks measuring executive control functions.

## 1.8 Overview of the thesis structure

The dissertation has been structured according to the chapters given below:

*Chapter 1: Introduction.* Introduction to bilingualism, and the concepts used in the thesis, including the Adaptive Control Hypothesis, executive control functions, a brief background on the relationship between bilingualism and executive control, the cognitive implications of language switching, and the outcome of studies focusing on the same. This chapter also focuses on the language scenario in India, and the key research highlighting the sociolinguistic and psycholinguistic perspectives of being bilingual in India. Finally, the objective and rationale of the study are presented, and why there was a need to explore the field.

*Chapter 2: Literature review.* Literature review of the seminal studies in the field of bilingualism and executive control.

*Chapter 3: Methodology.* A description of the methodology used in the experiments, including questionnaires, tasks, and analysis used.

*Chapter 4: Bilingualism and Task Switching.* Examines the relationship between bilingualism and switching. It expands on the three switching tasks performed: Magnitude/Parity bivalent task, Number/Letter univalent task, and Colour/Shape bivalent task. The performances in the tasks are statistically analysed, and the results are discussed.

*Chapter 5: Bilingualism and Working memory.* Investigates the relationship between bilingualism and working memory using the *N*-Back task, a commonly used measure of working memory performance. The performance of the task is analysed, and the findings are discussed.

*Chapter 6: Bilingualism and Inhibition.* Describes the relationship between bilingualism and inhibitory control. Three tasks are used for this purpose: Simon task, Stroop task, and Go/No-go task. The results are analysed, and the findings are discussed.

*Chapter 7: Bilingualism and Affective control.* Elaborates on the relationship between bilingualism and affective control with the help of two tasks: Emotional Stroop task and Emotional Go/No-go task. The results of the task are analysed, and the findings are discussed.

*Chapter 8: Conclusion.* The culmination of the findings, limitations and future implications.

## 1.9 Chapter summary

In this chapter, we set the stage for the thesis by outlining the themes as well as the objectives of the study. It first broke down the key concepts by providing an overview of the various executive control mechanisms and then tracing their role in higher-order functions. This was followed by a historical perspective on the research done on bilingualism over the past several decades, highlighting the evolution of the key theories and models in this field. Then, a discussion on the Indian linguistic scenario has been presented to emphasise the diverse and dynamic nature of bilingualism in such a society. By examining the nature of bilingualism in such a setting, along with its interaction with general cognitive faculties, this research aims to contribute to the broader understanding of how bilinguals navigate cognitive processes.

With this foundation in place, the following chapters will attempt to minutely examine this relationship and discuss the findings and possibilities that it yields. First, a more detailed review of the literature is presented, breaking down the current trends in this field. This is followed by the chapter that breaks down the methodologies used to pursue this research. The next four chapters will examine each of the executive control mechanisms that are described above and discuss the findings obtained. Finally, the conclusion chapter will discuss the combined findings, how this research contributes to the broader field, as well as future possibilities.

# 2 Literature review

## 2.1 Introduction

The thesis explores the relationship of bilingualism with non-linguistic factors such as the cognitive control mechanism. Understanding how this relationship came about is crucial. Studies on the relation between bilingualism and cognitive abilities have been conducted since the early 1920s to determine the effects that learning an extra language had on a child's mind. Known then as the "language handicap", there were consistent findings on the negative impact of bilingualism then. Over the years, studies have yielded mixed results when it comes to establishing a relationship between bilingualism and executive control. This thesis aims to explore the presence of a relation between the variability of being bilingual and the spillover effect that might have on general executive control mechanisms. This chapter, thus, justifies the need for such a study by breaking down the existing literature on the matter and then critically analysing the research gaps present, which this study will attempt to address.

## 2.2 Chapter Overview

This chapter reviews the existing literature on bilingualism and cognitive control with the aim of identifying and addressing the gaps in the literature. The chapter is logically divided across a total of five sections. The first section discusses studies that have looked at bilingualism and domain-general executive control, covering a broad scope of studies that have captured the changing mindset towards bilingualism and the results from said studies. The second section focuses specifically on the bilingual factor of interactional context and language switching mechanism, and its interaction with domain-general cognitive control. The third section follows, with studies exploring the influence of other bilingual factors. The fourth section provides a brief survey of the prominent literature on neurological studies on bilingualism and executive control. Fifth, we conclude with a review of the literature on studies done on affective control and the interaction between bilingualism and affective control. Research gaps present in the existing literature are discussed, justifying the need for the current study.

## 2.3 Bilingualism and Executive Control

In a review by Hakuta & Diaz (1985), a majority of studies found that bilinguals were linguistically deficient compared to their monolingual counterparts. They were shown to be deficient in articulation, had lower standards in written composition, made more grammatical errors and had a considerably reduced vocabulary.

Towards the end of the 1950s, studies were consistent in their findings, which showed that monolinguals performed significantly better than bilinguals on measures of verbal intelligence. The results were mixed on non-verbal intelligence, in that some showed monolinguals as superior, but the group differences on this variable were not consistent. However, things started changing from 1962 when, in their paper, Peal & Lambert (1962), compared 10-year-old monolinguals and English-French bilinguals living in Montreal on a variety of standard tests of intelligence: both verbal and non-verbal. The assumption, like that of their predecessors, was that monolinguals would show superior performance over the bilinguals in the intelligence tests. However, contrary to the findings of earlier studies, the results showed that bilinguals performed significantly better than monolinguals in most of the cognitive tests and subtests, specifically the subset of tests that required mental manipulation and reorganisation of visual stimuli or certain mental or symbolic flexibility.

Since then, studies have compared monolingual children with balanced bilinguals, and the bilinguals have shown advantages in concept formation, metalinguistic awareness, and flexibility in performing various cognitive tasks (a brief review by Hakuta & Diaz (1985)). The executive function develops dramatically during infancy and childhood (Munakata et al., 2013). In a study by Carlson & Meltzoff (2008), children between 4-7 years of age were divided into three language groups: English-speaking monolinguals, Spanish-English native bilinguals, and English speakers enrolled in second language immersive studies in either Spanish or Japanese. The children were tested on a battery of executive functions related tests, like Dimensional Change Card Sort, Simon Says, Attentional Network Task, etc. and it was found that the Spanish-English native bilingual speakers performed significantly better than the other two groups on the executive function battery. Similarly, another study, (Morton & Harper, 2007) administered the Simon task to monolinguals and English-French bilingual children to check for conflict resolution. The children were 6-7 years of age from identical ethnic and socioeconomic status (SES). This control over the ethnicity and SES was to determine if bilingualism was, in fact, the contributing factor to increased cognitive abilities. It was found that both monolingual and bilingual children performed identically in the Simon task. However, children from higher SES performed slightly better than those from lower SES. This study claims to be the first to compare attention control in bilingual and monolingual children from similar ethnic and socioeconomic backgrounds.

To check if the sociolinguistic context of language use had any impact on the bilingual cognitive advantage, Blom et al. (2017) did a comparative analysis of 3 groups of bilingual children, with a control group of monolingual Dutch-speaking children in the Netherlands. Aged between 6 and 7 years, the three bilingual groups consisted of: Frisian-Dutch, Limburgish-Dutch (both regional dialects) and Polish-Dutch children, all matched in non-verbal intelligence. They participated in two working memory tasks (verbal and visuospatial) and two attention tasks (selective attention and interference suppression). Bilingual children performed better than the monolingual group in the selective attention task. The bilingual cognitive advantage was most clearly pronounced in Frisian-Dutch bilinguals, less so in Limburgish-Dutch children. A subgroup of Polish-Dutch children who were relatively proficient in Polish also showed a significant cognitive advantage. However, no bilingualism effect was seen in verbal and visuospatial working memory tasks.

In Poarch (2018), a previous 2012 study was replicated to scrutinise the participants' conflict monitoring and inhibitory control. Unlike the previous study, the age range was extended to include participants between 5 and 13 years of age, who were either German monolinguals who were second-language learners of English or German-English bilinguals or multilinguals who were German-Other language-learners of English as a third language. It was shown that multilinguals and monolinguals differed significantly in their ability to resolve conflict. This result agreed with the view that enhanced executive function in multilingual children came from their permanent need to monitor, control and shift between languages.

A study by Johann et al. (2022) measured different executive control functions and fluid intelligence of monolingual and bilingual elementary school children and compared the performance in various tasks in an attempt to establish a relationship between executive function and intelligence of monolinguals and bilinguals. The L1 of the participants was German, and the second language of the participants was varied. The study had two tasks each, for working memory, inhibition, flexibility and intelligence. The working memory tasks were Corsi-like task and *n*-back task. Inhibition tasks included Go/No-go task and AX-CPT. For shifting and flexibility, there were cued task switching and task switching with alternating runs. Results showed that while executive function and intelligence were significantly related in both language groups, the relationship was found to be stronger in the bilingual group. However, no latent performance differences were found in executive control tasks or intelligence tasks between the two language groups.

Karimi & Hosseini Rad (2021) compared performances of monolingual and bilingual children and adolescents in Iran to observe the effect, if any, of bilingualism on inhibitory control and monitoring processes. The participants were all natives of Iran, whose mother tongue was Persian. The second language of the bilingual participants was English, which they picked up through formal education. The participants were made to perform two versions of the Flanker task- the adult version and the child version. The results showed that while the bilingual groups had faster reaction times on incongruent trials than the monolingual groups, they were not generally faster than the monolinguals. This showed an enhanced ability in inhibitory control and conflict resolution, thus proving the presence of a bilingual advantage over monolinguals.

A year-long longitudinal study by (J. Chen et al., 2023a) investigated the relationship between executive function and the second language vocabulary of Uyghur-Chinese bilingual pre-schoolers in China. It specifically focused on the receptive and expressive vocabulary of the participants, and the three components of executive function, namely, working memory, cognitive flexibility, and inhibitory control. The behavioural tasks performed included Forward Digit Span Task, Backward Digit Span Task, Corsi Block-Tapping Task, Head-to-Toes Task, Head-Toes-Knees-Shoulders Task, Dimension Change Card Sorting Task- Standard version, and Border version, and Non-verbal intelligence Task. The tests were administered twice with a gap of a year in between. Results showed that there exists a relationship between L2 vocabulary and executive functions, primarily with respect to flexibility and inhibitory control, but not so much with working memory. This relationship, however, was not universal across receptive and expressive vocabulary. Performance in inhibitory control and cognitive flexibility tasks significantly positively predicted Mandarin receptive performance a year later. Performance in Mandarin expressive vocabulary significantly positively predicted performance in inhibitory control and cognitive flexibility one year later. However, the predictive relationship between expressive and receptive vocabulary and working memory performance was found to be insignificant.

The transition from adolescence to adulthood brings forth a diversity in developmental trajectories of the various executive functions, showing a linear and non-linear development of executive functions. By the time one reaches early adulthood, inhibition skills show improvement from late adolescence to adulthood. One reason for this could be synaptic pruning, which helps form more efficient neural networks (Taylor et al., 2015). A study by Prior & Macwhinney (2010), explored the possibility of lifelong bilingualism leading to enhanced efficiency in the ability to shift between mental sets, in short, a comparison of their cognitive flexibility. The participants were university students who were English-speaking monolinguals and Language X-English-speaking bilinguals whose other languages included Mandarin, Korean, Spanish, Russian, Bengali, and so on. The bilinguals incurred a reduced switch cost as compared to the monolinguals in the task-switching paradigm, but there was no difference in the differential cost of performance in mixed-task and single-task blocks. Bilinguals aged 18 to 27 years, who were early and proficient Catalan-Spanish bilinguals, were examined in a study by Calabria et al. (2011) to understand if the switch cost pattern in language switching tasks carries over to the non-linguistic switching task. The participants showed symmetrical switch costs in the linguistic switching task, but not in the non-linguistic switching task, where an asymmetrical switch cost was observed throughout. This proved that linguistic cognitive abilities have not completely carried over to the domain-general executive functions. In the study by Tao and colleagues (2015), undergraduate monolingual English speakers, Spanish-English and Mandarin-English bilinguals in California were given standardised tests to measure and compare their task switching ability. This was done to measure the relationship, if any, between bilingualism and task switching. The Spanish-English bilinguals exhibited smaller switching costs in task switching than monolinguals, proving their advantage in task switching. The Mandarin-English speakers also exhibited a statistical significance, although it was slightly smaller. This study tentatively claimed that there might be variation in cognitive task performance across different language combinations. In a study by Segal et al. (2019), university-level Spanish-English bilinguals were tested to see if linguistic conflict while language switching reveals similar patterns of switching cost across the response time (RT) distribution when comparing with conceptual conflict and perceptual conflict. It was revealed that bilinguals who responded faster and showed smaller mixing cost in language tasks, showed larger switch cost in colour-shape task (a non-linguistic task). These results indicated that different measures of switching costs even in tasks with very similar designs, vary in their switching ability measurement, be it between tasks, or even between different trials in the same task.

S. Li et al. (2021) interestingly explored the effect of executive control functions on language control, specifically two components of inhibitory control- interference suppression and response inhibition. In two separate studies, the participants were unbalanced Chinese-English bilinguals with a higher proficiency in Chinese. They were asked to perform a bilingual language switching task and a general executive control task. In the first experiment, the participants had to perform Simon task and cued language-switching task. In the cued language-switching task, the participants were asked to name the picture presented in the language indicated by the colour of the frame of the picture. In the second experiment, the participants performed the same linguistic task and Go/No-go task for inhibitory control measure. In experiment 1, results showed that in linguistic switching task, predictably, the response timing the switch trials were longer than for non-switch trials, in both Chinese and English. There was also a reversed language dominance effect, meaning that the unbalanced bilinguals were slower to respond in L1 as compared to L2. A negative correlation was found between L1 switch cost and Simon effect. While the Simon effect significantly predicted the asymmetry in switch costs, though there was no overall asymmetry in switch cost. However, there was no correlation found between Simon effect and reversed language dominance effect. Results in experiment 2 showed that response timings for the Go trials in the Go/No-go task significantly predicted the reversed language dominance effect. Specifically, faster

RTs for go trials were associated with greater reversed language dominance effects. Together these findings suggested that interference suppression aids local level language control, whereas response inhibition impacts global level language control in bilinguals.

Towards late adulthood, the frontal lobes, which house the executive functions, start to show significant atrophy (Von Hippel, 2007). With gradual shrinkage in brain volume, the cognitive functions of the brain start to show depreciation.

Champoux-Larsson & Dylman (2021) compared performances of monolinguals and bilinguals in a Simon task performance. Performance of the bilingual participants were measured using various bilingual factors to determine which of the factors showed a relationship with the general inhibitory control performance. The participants had English as their L1 and the bilingual participants had various different languages as their L2. The bilingual factors measured were either of continuous or dichotomous nature. Participants had to respond to the Language and Social Background Questionnaire (J. A. E. Anderson et al., 2018) and other questionnaires to get scoring for each of the factors to be investigated. These factors included: CFS (Composite Factor Score, a general score obtained from the questionnaire), HUP (Nonnative Home Use and Proficiency score, for second language use and proficiency), LSU (Nonnative Language Social Use score for social use for L2), age of acquisition, and frequency of code-switching. Based on the responses to the questionnaires, the participants were distributed, and grouped accordingly, to be analysed based on the various independent variables. Results showed that when the participants were divided into monolinguals and bilinguals based on CFS, the performance of the bilingual group was significantly slower. When LSU was considered as a dichotomous variable, monolinguals had significantly faster performance in both congruent and incongruent trials than bilinguals. When the LSU was used as a continuous variable, bilinguals had slower performance but in congruent trials only. When age of acquisition was considered as a dichotomous variable, there was no significance in the performance of the bilinguals, however when considered as a continuous variable, age of acquisition significantly predicted the performance in congruent trials. HUP score and code-switching as variables showed no predictions whatsoever. Thus, while what variable is considered is important, how this variable is measured is also important.

Thus, the literature reflects the presence of a relationship between bilingualism and executive control across the lifespan, from children, to young adults, as well as older adults. The results in studies examining this relationship have not all been positive and have been mixed. The next section will provide a brief literature review on studies that have explored the specific relationship between bilingual interactional context and the executive control.

### 2.3.1 Bilingualism and Executive control: Bilingual interactional context

This section explores how a specific component of being bilingual, namely the interactional context, interacts with the executive function, with focus on the Adaptive Control Hypothesis and the results that came out of it. Since the inception of the Adaptive Control Hypothesis, several studies have tried and investigated the presence of this phenomena. Results with respect to the ACH have been mixed.

Hartanto & Yang (2016) investigated the task switching performance of bilinguals in Singapore by doing a comparative study between bilinguals in Single Language Context (SLC) with bilinguals in Dual Language Context (DLC) on their task switching performances. As previously mentioned, SLC bilinguals speak only one language in one environment and rarely switch as opposed to DLC bilinguals who switch between languages in one context. Their aim was to see if the interactional contexts of the bilingual university students would affect their performance in task switching task. In a typical colour-shape switching task, the DLC bilinguals showed faster response in switch trials than in repeat trials as compared to SLC bilinguals. Their investigations revealed that while participants of Dual Language Switching context did have a smaller switch cost, there were no significant results in mixing costs nor for accuracy.

C. Barbu et al. (2018) divided bilingual adults they were studying into High Frequency Language Switchers (HFLS) and Low Frequency Language Switchers (LFLS) to study the impact their language switching had on attention and executive functioning. The participants, who were between the ages of 18- 43 years, had French as either their L1 or L2 and they spoke a variety of other languages such as German, Romanian, English, and Dutch. The results of the tests showed no significant difference in terms of age, socio-cultural level, receptive vocabulary skills, and self-rated second-language proficiency, they showed a significant group difference in cognitive flexibility (an executive function) with HFLS performing better than LFLS, but no significant group difference in response inhibition and alerting tasks. Soveri et al. (2011), examined if language switching plays any role in better executive functions among Finnish-Swedish bilinguals between 30 and 75 years of age. They were simultaneous bilinguals who learned both languages before the age of 7 roughly and had used both languages throughout their lives. They were administered a number of tests to examine their performance in various executive functions like inhibition, updating and set shifting. It was found that age of the participants, their age of acquisition of the L2 and the language switching frequency all play a significant role in proper functioning of the executive control system.

Ooi et al. (2018) studied the impact that switching behaviour had on attention, by examining four groups of bilinguals in Edinburgh and Singapore, due to the contrasting sociolinguistic environments of these two regions. The four groups included: monolinguals in Edinburgh, non-switching late bilinguals in Edinburgh, non-switching early bilinguals in Edinburgh, and switching early bilinguals in Singapore. The participants performed two attentional control tasks, namely the Attention Network Task (ANT) (J. Fan et al., 2002) and the subtest of Elevator Reversal from the Test of Everyday Attention Battery (Robertson et al., 1996). Results showed that Singaporean switching early bilinguals performed better in conflict resolution in ANT, the Edinburgh late bilinguals performed better on attentional switching in Elevator reversal. These results suggested that the interactional context of bilinguals could have an effect on the performance of attentional control mechanisms.

Pot et al. (2018) investigated which aspects of being multilingual was responsible for the cognitive advantage, under what conditions and for which population. They examined older adults in Northern Netherlands perform common executive control tasks like Flanker task, Wisconsin Card Sorting Task (WCST). An interesting aspect of this study was that it considered bilingualism of the participants along a continuum instead of grouping participants based on their bilingual profile. Results showed that while the degree of contextual language usage had no effect in the performance in the WCS Task, it did affect the performance in Flanker task. It was found that those using more than one language, especially their L2, across different social contexts, were found to have a smaller Flanker effect score.

Beatty-Martínez et al. (2019) examined bilinguals who spoke Spanish and English, and were highly proficient in both. The participants were Spanish-English bilinguals living in 3 different regions, using 3 different contexts of bilingualism. The three contexts were: Separated context for bilinguals in Spain where they use each language for specific environment, and rarely switch between languages within a conversation, the Integrated context for bilinguals in Puerto Rico included participants who frequently used both their languages and switch between languages in certain contexts of their everyday life, and finally the Varied context for bilinguals in the US which comprises of participants speaking specific language in specific context, but also included code-switching among other Spanish-English bilinguals. The aim of this study was to see how these different contexts affected the linguistic performance of the bilinguals as well as performance in general executive function tasks. Participants were made to perform Category verbal fluency task, Picture naming task among linguistic tasks, and the AX version of the Continuous Performance Task (AX-CPT) for the non-linguistic task. Results showed that while there were no significant differences in the processing speed among the three groups in the AX-CPT, there were differences among them in the recruitment strategy of the cognitive processes utilised. Separated context bilinguals relied lesser on context processing and instead showed greater engagement of reactive control processes. Varied context bilinguals on the other hand, relied more on contextual information, and showed greater engagement of proactive control processes. The processing preferences of the integrated context bilinguals were shown to be roughly in the middle of the other two groups.

Hartanto & Yang (2020) looked into the relationship between bilingual interactional contexts and executive function among bilingual young adults in Singapore. Using the revised version of the Bilingual Interactional Context Questionnaire (Hartanto & Yang, 2016), the participants were divided into 3 groups based on their score on various interactional contexts: Single-language context, Dual-language context, and Dense code-switching context. They were then made to perform nine executive function tasks to look at three primary executive functions: inhibitory control, working memory and task switching. The tasks performed included modified arrow flanker task, modified Eriksen flanker task, modified colour flanker task, colour-shape switching task, magnitude-parity switching task, animacy-locomotion switching task, rotation span task, operation span task, and symmetry span task. The results showed that for inhibitory control, dual and single language bilinguals did not show better inhibitory control or goal maintenance abilities, rather dense code switching had significantly better inhibitory control and goal maintenance. In the tasks that measured working memory performance, there were no associations found between interactional contexts and task performances. Finally, for task switching performance, bilinguals with greater exposure to dual language context had a better performance in task switching than those in single language context. Those with dense code-switching context, did not predict task switching performance.

Struys et al. (2019) looked at bilinguals with varying L2 proficiency and degree of recent language exposure and compared their performance in various domain-general cognitive control abilities. Participants were Dutch-French bilingual young adults who performed the Simon task, along with 2 linguistic tasks, namely, the Single-language verbal fluency task, and the Bilingual categorization task. Results indicated an overlap in performance of participants in Simon and Bilingual categorization task which pointed to an overlap in control requirements. Nevertheless, the performance in Simon task was only related to a forward switch cost, from L1 to L2, but not with a backward switch from L2 to L1.

Lai & O'Brien (2020) investigated the relationship between switching behaviour and verbal and non-verbal cognitive control, by examining 5 of the cognitive control processes mentioned by the

Adaptive Control Hypothesis, namely goal maintenance, selective response inhibition, interference suppression, and task engagement and disengagement. English-Mandarin bilinguals living in Singapore performed Stroop task for verbal task and Global-Local task for non-verbal task. Based on self-reporting, the participants indicated their language switching contexts- single-language context, dual-language context and dense code-switching context, and switching behaviours- inter-sentential or intra-sentential switching. While the impact of control exerted in the dual language processing was reflected in the performances, it was only found in the verbal Stroop task, and just marginally significant.

In an attempt to test the Adaptive Control Hypothesis, Kałamała, Szewczyk, et al. (2020) looked at the bilingual language usage pattern and cognitive control performance, focusing specifically on response inhibition. Interestingly this paper focused only on Dual-language context and honed in on the intensity of DLC experience. Thus, participants included unbalanced Polish-English adult bilinguals whose language usage patterns were determined using the Patterns of Language Use Questionnaire developed in this study and the Bilingual Interactional Context Questionnaire (Hartanto & Yang, 2016). The tasks they performed included various response inhibition related tasks such as Stroop task, Go/No go task, Antisaccade task, as well as the Stop signal task. However, there were no significant relationships that were shown between Dual language context intensity and performance in the selective response inhibition tasks.

Paap et al. (2021) also examined the claim of ACH of enhanced cognitive abilities by reanalysing previously published data on young bilinguals of varying language pairings, across various measures of executive function, where no significant results were found. The first of the two studies reanalysed, (Paap et al., 2019), compared monolinguals and bilinguals in four executive function tasks, Simon task, Stroop task, Vertical Stroop task, and Flanker task. The participants were divided into 6 groups based on their language switching performance: pure monolinguals, other monolinguals, Single-language context (SLC), Dual-language context (DLC), Dense code-switching context (DCS), and other bilinguals. Reanalysis of the data showed that while there were no significant differences in performances between the various language groups, DCS did have better interference control than SLC or DLC, both of which showed identical means. The second study that was reanalysed (Paap et al., 2018) had university students perform colour-shape switching task, conjunctive visual search task, spatial Stroop task, and morphing ambiguous figures task. The results of the reanalysis showed that the DLC did not outperform the other groups in any of the measures, thus not aligning with the premise of the ACH.

A study by X. Han et al. (2022) examined how code-switching behaviour affects the cognitive control functions of inhibition and shifting. The participants were Mandarin-English bilingual adults living in various English-speaking countries such as Australia, Canada, Ireland, US, and UK. The code-switching habits of the participants were measured using Bilingual Switching Questionnaire (BSWQ) (Rodriguez-Fornells et al., 2012) and Language Social Background Questionnaire (J. A. E. Anderson et al., 2018). The tasks to be performed included bilingual picture-naming task, colour-shape switching task, and Go/No-go task. The analysis showed that frequent language switchers had better performance in verbal as well as non-verbal switching task. The performance of the participants in bilingual picture-naming showed that their experience of using their languages in separate contexts provided them with better maintenance of the target language, while inhibiting interference from the competing language, thus supporting the Adaptive Control Hypothesis partially in its claim. In the cued language switching performance participants engaged in Dual-language and Dense code-switching contexts performed better than Single-language context participants in reactive inhibition on linguistic interference in the task. However, there were no significant relations between the participants' code-switching and nonverbal switching performance. As for the performance in Go/No-go task, dense code-switching participants were better at withholding habitual responses in No-go condition as compared to the other groups.

Ng & Yang (2022) examined how the code-switching patterns of bilinguals would shape many aspects of cognitive control, namely interference control, salient cue detection and opportunistic planning, while controlling for various other factors such as age, gender, parental educational level, language proficiency, socioeconomic status, etc. So, English-Chinese university students in Singapore performed tasks such as verbal opportunistic planning task, and attentional Network Test for Interaction and Vigilance (ANTI-V). A language background questionnaire, adapted from (Marian et al., 2007) and (P. Li et al., 2014), was used to determine the participants' linguistic history and the Bilingual Interactional Contexts Questionnaire adapted from Hartanto & Yang (2020) to establish the participants' language usage pattern and divide them into 3 groups, Single-language context, Dual-language context and Dense code-switching context. Results showed that DLC was not associated with interference control or salient cue detection, however, showed significantly reduced response timings for opportunistic planning. On the other hand, the DCS was showed to be positively associated with verbal opportunistic planning, but negatively associated with interference control and salient cue detection, thereby abiding with the premise of the ACH.

A study by X. Han et al. (2023) tested the Adaptive Control Hypothesis by examining how the various language interactional contexts regulates cognitive control in language comprehension of

Chinese-English bilinguals. The task they performed was a Flanker task. The participants were made to listen to 3-minute conversations alternated with Flanker task performance, followed by a quiz based on the dialogue they had just previously listened to. The 3-minute conversations had four variations: Chinese only, English only, Chinese-English dual language, and in dense code-switching. The quiz was created to compare the participants' performance after listening to dialogues in various interactional context. These questions in each session matched the linguistic context of the dialogue they were based on. Results showed that the performance of the participants in dual-language context showed significant improvements compared to their performance in English language context and dense code-switching context, thus providing evidence for Adaptive Control Hypothesis' claim that interactional context has some influence on cognitive control function of inhibitory control.

In their study, Gosselin & Sabourin (2023) examined the relationship between a bilingual's code-switching habits and their inhibitory control performance. The participants were French-English adults originating from a Dual-language context environment. This paper considers dual-language code switchers as language athletes, in that by regularly activating and suppressing their languages, they are training their executive function, just like athletes get their training. The participants were made to perform a language-specific task, a bilingual Stroop task, and a domain-general task of Flanker task. Their code-switching behaviour was measured using the Bilingual Switching Questionnaire (BSwQ) (Rodriguez-Fornells et al., 2012) which revealed that while French-dominant and English-dominant bilinguals showed so significant difference in overall switching rate, the participants dominant in French switched to French more frequently, whereas English-dominant participants had more French to English switches. They also computed the language entropy statistics (Gullifer & Titone, 2020), which examined the linguistic diversity of a given environment. The value obtained was consistent with a dual-language interactional context, shown to be typical linguistic environment of Ontario, where this study was situated. The results of the study showed that on one hand the French trials in Stroop task yielded no significant results. On the other hand, the participants who reported more habitual French to English code-switching were shown to have better inhibitory control and goal monitoring performance in both the tasks.

(Yang et al., 2023) predicted that the dual language context would positively predict performance in inhibitory control and shifting, but not updating among bilingual older adults. Participants were made to perform the Stroop task, backward digit span task, and Stop and Go Switch Task, along with answering a revised version of the Bilingual Interactional Contexts Questionnaire adapted from Hartanto & Yang (2020) to get a sense of their language switching habits and categorise them accordingly as Single-language context, Dual-language context and Dense code-switching context.

Interestingly, it was found that Dense Code-Switching was found to predict a significantly better performance in the overall executive function performance, however not in the individual aspects if the executive function separately. Meanwhile, there were no associations found between dual language context and inhibitory control, updating, or shifting.

This section covered a brief literature review of studies that have explored the relationship between executive function performance and the interactional context habit of bilinguals. It has examined how this facet of being bilingual has influenced various executive functions. This literature also examined the studies that incorporated the Adaptive Control Hypothesis (Green & Abutalebi, 2013) and the results that were obtained. Very few studies have investigated the performance of the bilinguals in the control processes mentioned by the ACH (Hartanto & Yang, 2020; Kałamała, Szewczyk, et al., 2020; Lai & O'Brien, 2020; Ng & Yang, 2022), and the results they found have been mixed. In (Hartanto & Yang, 2020), Dense code-switching context showed better inhibitory control, and goal maintenance abilities but not Single or Dual language contexts. Similarly, in (Kałamała, Szewczyk, et al., 2020), no significant relationship was found between response inhibition performance and Dual language-context group. Lai & O'Brien (2020) looked at goal maintenance, selective response inhibition, interference suppression and task engagement and disengagement, however found the DLC group perform better only marginally significantly. In Ng & Yang (2022) DLC was not associated with better performance in salient cue detection and interference control, but showed reduced RTs for opportunistic planning, however, as per the ACH, Dense code-switching are supposed to show heightened performance in this process. This thesis, therefore, will attempt to understand the role of interactional context and the possibility of its spillover effects on general executive functions, through the mechanisms of ACH, trying to understand the reason for mixed results mentioned in the previous studies. The next section will very briefly examine recent studies that have explored a relationship between bilingualism and executive control, through various other bilingual factors.

### 2.3.2 Bilingualism and Executive control: Other bilingual factors

This section looks at studies that have explored the possibility of a relationship between executive control performance and various other factors of being bilingual such as second language proficiency, language varieties, presence of an interlocuter, etc. For reasons of brevity, representative studies are discussed, with references to more.

*Second language proficiency*. Studies focusing on the proficiency as a variable to interact with cognitive control among code-switching bilinguals. One such study was carried out in Algeria (Kheder & Kaan, 2021), and explored the relationship between L2 proficiency and cognitive control. It examined the effect of frequency of daily dense code-switching and second language proficiency on cognitive control, and if this effect is separate or interactive. So Arabic-French Algerian bilinguals who were university students performed Simon task. Their language usage habits were determined using the Assessment of Code-Switching Experience Survey (ACSES) which gave rise to scores on a 1-7 scale in 5 different components. The results showed that those bilinguals that frequently code-switch showed lesser errors, and improved accuracy rate over trials showing smaller Simon effect. Highly proficient frequently code-switching bilinguals were better at conflict resolution, thus showing that proficiency also plays an important role.

This effect was examined in adult learners learning a second language (Luque & Morgan-Short, 2021), in this case, Spanish by examining their performance in Flanker task and AX-CPT task, as well as working memory tasks such as O-Span task, R-Span task, and Sym-Span task. Results showed the presence of a significant relationship between second language proficiency and performance in cognitive tasks, as well as speed of processing. This was specifically seen in the reactive control process through the AX-CPT performance.

*Performance of interpreters.* A study by Henrard & Van Daele (2017) compared the performances of interpreters, translators and monolinguals in executive control performance. The participants had to do the Reaction-time task, Letter Memory task adapted from (Morris & Jones, 1990), antisaccade task, Plus Minus task, and Brown-Peterson task (Peterson & Peterson, 1959). Results showed interpreters and translators performed better than monolinguals in all the tasks, and the interpreters showed better performed than the other two groups in Reaction-time task, Letter Memory task, and antisaccade task, thus reporting an interpreter advantage in executive control performance.

Nour et al. (2020) compared the working memory performance of professional as well as student interpreters. The first experiment looked at the effect of interpreter training on the working memory and short-term memory of translation students in a longitudinal study. Majority of the students' L1 was Dutch, others had French, their L2 included French, English, and Dutch, etc. The students were divided into two groups- interpreting and translating. Tasks performed included Reading Span Test, and Digit Span Test. Students were tested at the start of their Master's programme, and then again, 9 months later, at the end of the programme. The second experiment added professional interpreters and compared their performance with that of the participants in the previous experiment. They performed the same tasks as those in the first experiment. The results showed that there was no significant difference in performance between the two groups before and after training. There was some training-related improvement in working memory performance, but not in short-term memory performance. Professional interpreters displayed better performance than translation students but not interpreting students, in both working memory and short-term memory performance.

*Presence of interlocuters.* Bhandari and colleagues (2020) investigated how the presence of interlocuters impact the performance of bilinguals in executive control functions. Telugu-English bilinguals were shown monolingual, bilingual and neutral interlocuters and were asked to perform attention network task (ANT). The bilingual participants were divided into high-proficient and low-proficient bilinguals based on their L2 proficiency. Results showed that high proficient bilinguals showed higher executive control, demonstrating faster performance than low proficient bilinguals but only in mixed condition of the task, which required higher conflict monitoring.

A study by Rafeekh & Mishra (2021) examined the hypothesis that context leads to linguistic as well as non-linguistic cognitive control settings in presence of interlocuters. The premise was, that as per the interlocuter's language proficiency- categorised into 3 types, namely Balanced (both L1, L2, 50%), Unbalanced (L1 90%) and Neutral (unknown language identity)-high L2 proficient participants will show better conflict resolution performance in front of balanced interlocuters than low L2 proficient bilinguals. Malayalam-English bilingual university students participated in this experiment. Language control measures included language questionnaire, online vocabulary test WordORnot, Semantic Fluency Task, and Object Naming Task. The cognitive task performed was Flanker task. Results showed that presence of various different interlocuters influenced the Flanker task performance. High L2 proficient bilinguals were generally faster at the task. With balanced interlocuters, high L2 proficient bilinguals had faster RTs and smaller conflict effect, thus showing how presence of interlocuters and participants' knowledge of language dominance triggers specific control mechanisms. The next task had the same premise but included both, high and low level of conflict in Flanker task. The Malayalam-English bilingual participants were divided into two groups: High L2, and Low L2 participants. It was found that the high L2 proficient bilinguals were faster in the presence of balanced interlocuters in both high and low monitoring conditions. On the other hand, low L2 proficient bilinguals had lower conflict effect in low monitoring condition in the presence of an unbalanced interlocuter. However, no interlocuter effect was found on high monitoring condition. Thus, this study showed how the presence of interlocuters with varying L2 proficiency affect cognitive control performance of bilinguals.

*Diglossia.* Diglossia is varieties of a language that are spoken in completely separable contexts. As per the Adaptive Control Hypothesis, this would fall under Single-language context usage. The study by Alrwaita et al. (2024) examines the effect that diglossia has on cognition of bilinguals, by comparing cognitive control performance between English monolinguals and Arabic diglossics. The two Arabic varieties were standard variety and spoken variety. Tasks performed were Flanker task, Stroop task, and colour-shape task. The aim of this study was to see if diglossic participants would perform similar to monolinguals. The results did not show any difference in performance between the monolinguals and the diglossic participants across task levels, in any of the tasks. Interestingly, in fact, the monolingual participants seemed to have shorter overall RTs.

*Performance of trilinguals.* This study (Madrazo & Bernardo, 2020) compared the inhibitory control performance of bilinguals and trilinguals in an attempt to investigate the hypothesis that both the groups would have similar performance due to both having identical cognitive processes that comes from suppressing information from irrelevant languages, regardless of the number of irrelevant languages. The participants were university students who were English-Filipino bilinguals and Chabacano-English-Filipino trilinguals, Chabacano being a Philippine Creole Spanish. the participants were made to assess the proficiency of their languages in production and comprehension skills using an extemporaneous speaking test and an essay test. To test their inhibitory control performance, the participants performed the Go/No-go task and Sustained Attention to Response Task (SART). Results showed that there was no difference in performance between the bilingual and trilingual participants in the Go/No-go task. Similarly, the participants had no difference in performance in SART either. Thus, this study aligned with the hypothesis of there being no difference in inhibitory control performance between bilinguals and trilinguals.

### 2.3.3 Bilingualism and Executive control: Neurological studies

A study by Luk et al. (2010) compared the performance of monolinguals and bilinguals in their inhibitory control performance using fMRI. It specifically looks at performance in inhibitory control components of response inhibition and interference suppression. The participants were English monolinguals and bilinguals with varying L1 and English as L2, who performed a modified version of the Flanker task which captured the performance in response inhibition and interference suppression. Results showed that young adults with varying bilingual experience seemed to have varying neural correlates while performing non-verbal cognitive tasks. While behavioural data of the two groups did not show significant difference in speed and accuracy, they did show different activation patterns while performing trials in the Flanker task. Results showed that in the No-go trials, both bilinguals and monolinguals showed activation in the same areas that represent general cognitive control network that is utilised for response inhibition and interference suppression and included the right inferior frontal regions. However, monolinguals and bilinguals showed different region activation in congruent and incongruent trials. It was found that in monolinguals, the incongruent and no-go trials were taken care of by two different networks, whereas a wider network covered both, incongruent trials and No-go trials.

Weissberger et al. (2015) had their participants go under an fMRI scanner to check the extent the control mechanisms share across domains of various functions. College-aged English-Spanish bilinguals were asked to complete a language switching task and a colour-shape task while in an fMRI machine. While there was considerable overlap in brain regions underlying language and colour-shape tasks, there were also differences across domains implying only a partial overlap in the mechanisms that control language and task-switching.

To understand the processing difference between monolinguals and bilinguals in linguistic and non-linguistic switching task, Timmer et al. (2017) looked at English monolinguals and English-French balanced bilinguals to examine their performances through electrophysiological (EEG) measures. They were made to perform non-verbal and verbal switching task. Behavioural analysis showed that bilinguals were more accurate than monolinguals in the mixed block in non-verbal switching task, monolinguals were slower than bilinguals in the language switching task. ERP data showed that there was more overlap in brain region activation for the two tasks for the bilinguals than for monolinguals, implying that the two tasks might appear similar for the bilingual brain.

An fMRI study by Yuan et al. (2021) examined the two-way relationship between bilingual language control and cognitive control, based on the immediately adjacent influence on the neural connectivity level. Chinese-English bilingual participants were recruited and made to perform two tasks, a language switching task and a task switching task. The participants were divided into two groups, one group performed the language switching task first followed by the task switching task, the other group performed the task switching task and then the language switching task. Results showed that when just the language switching task was performed, only the right thalamus was found to be activated as a single hub, whereas when the language switching task was performed after the task switching task, the neural network was wider, both the dACC/pre-SMA and the right thalamus showed activation. on the other hand, performing task switching task after the language switching task showed that also showed increased activation as compared to when cognitive task was performed first. Performing the language switching task first showed increased nodal activity in dACC/pre-SMA and the right thalamus. Thus, these results show how both language control processes and cognitive control processes have cross-task adaptation and multiple cognitive processes overlapping.

In an Electrophysiological (EEG) study, Carter et al. (2023) examined how differential bilingual experience may have an effect on the neural architecture of attentional control as well as on attentional control performance. The participants were English monolinguals and bilinguals with varying L1 and English as L2. The tasks performed were two interference suppression tasks, Simon task and Flanker task. Results showed the effect of differential bilingual experience on interference suppression performance, but only in Flanker task, and not in Simon task. Longer usage of two languages showed negative correlation with interference effect. This in turn activated the bottom-up control measures (specially P3). With the increasing frequency of language switching and diversity in language usage in bilinguals, reduced interference effects were found in top-down control measures, with smaller midfrontal theta power effect. This showed how frequency of language switching seemed to have trained the executive control, specifically in the function of proactive top-down control, leading to better interference suppression in Flanker task. This lines up with the assumption made by the Adaptive Control hypothesis

### 2.3.4 Bilingualism and Executive control: Affective control

This thesis has also investigated affective control among (bilingual) young adults. Thus, the affective control performance of the participants was investigated using emotional versions of the executive control tasks, to compare performances in affective and non-affective environments. This section briefly looks at the current literature scenario of research done on the affective control processes of bilinguals. First, a brief review of the affective control studies followed by a closer look at the studies exploring the relationship between various factors of affective control and bilingualism.

*Affective control.* Kahan & Hely (2008) looked at whether valence and frequency of emotion- words will affect the response timings (RT) of the participants. Results showed that Low Frequency negative words showed a slower response timing than any other conditions. Agustí et al. (2017) investigated the performance of younger and older adults in words and faces with emotional valence. It was found that words with positive valence had more Stroop interference than words with negative valence. Similarly, response to faces with positive valence had higher Stroop interference than faces with negative Stroop interference. Kar et al. (2018) examined the proactive and reactive control effects in face-word Stroop task, for positive valence and negative valence. Results showed that when the previous trial showed negative emotion had a greater effect on proactive control than positive emotion did. When the sad faces appeared in the previous trial then it resulted in reduced Stroop interference when it was a happy face in the next trial. Thus, proving that emotional valence influences both, proactive and reactive control.

Dresler et al. (2009) examined the performance of healthy participants in emotional Stroop task to examine if it was word valence or word arousal that caused emotional interference effect. It also examined the influence that trait and state anxiety might potentially have on emotional interference. The task consisted of neutral words and emotion words presented to the participants, where the participants had to ignore the word and respond to the colour of the stimulus on the screen. The emotion words used as stimuli were both negative and positive words. Results showed than response timing was slower for emotion words compared to neutral words. It was also found that emotional interference effect was influenced by word arousal, and not word valence. State anxiety, not trait anxiety, was found to be associated with emotional interference effect, it was heightened in high state anxiety subjects.

In an EEG study Megías et al. (2017) examined if individual emotional intelligence (henceforth EI) influences the cognitive control ability of healthy individuals. Based on their responses to the Mayer-Salovey-Caruso Emotional Intelligence Test (MSCEIT), the participants were divided into two groups: High EI group, and Low EI group. The task they performed was emotional Go/No-go task, while their brain activity was recorded by EEG. The participants were shown faces of three categories, neutral, happy and fear faces. The participants had to respond to the stimuli on the screen in Go trials and refrain from responding in the No-Go trials. Results showed that Go trials had higher accuracy levels than No-go trials. Electrophysiological results showed that No-go trials had larger N2 and P3 as compared to Go trials, indicative of increased cognitive control. When it came to comparing performances of high EI and low EI, participants with high EI had a larger N2 than those with low Emotional Intelligence, showing that participants with high EI had greater capacity for cognitive control.

In another event-related potential (ERP) technique study, J. Liu et al. (2022) examined the effect of valence while processing emotion-laden words and emotion-label words in emotional categorisation task (ECT) and emotional Stroop task (EST) in Chinese speaking participants. In emotional categorization task, the participants had to judge the valence of the words, whereas in emotional Stroop task, they had to respond to the colour of the word, ignoring the emotional content. Behavioural results aligned with previous studies, with longer response timings associated with emotion-laden words than emotion-label words. Electrophysiological studies showed that in the early perceptual processing stage, negative words were shown to have produced an amplified N170 than positive words. Then, in the second processing stage, negative emotion-laden words prompted enhanced P2 and Early Posterior Negativity (EPN) compared to negative emotion-laden words. On the other hand, positive emotion-laden words had enhanced EPN compared to positive emotion-label words. Next, in the elaborate processing stage, emotion-laden words had larger N400 and early LPC than emotion-laden words during explicit processing of stimuli. While larger N400 effect was found in implicit word processing, negative words had enhanced late LPC than positive words during explicit processing.

*Affective control and bilingualism.* S. Han & Lee (2013) compared monolingual and bilingual children in cognitive and affective perspective-taking ability performance. The participants were 4-year old and 5-year old Korean monolinguals, and Korean-English bilinguals aged 4-5 years living in South Korea. The tasks included a cognitive perspective-taking task and affective perspective-taking task. The task was to look at a series of pictures in sequential order. Then some pictures were removed and the child was asked how their friend would tell the story if they saw only the remaining pictures. Scores ranging from 0 to 2 were given out depending on how the participant managed to retell the story from the friend's perspective, higher the score, higher the child's cognitive perspective-taking ability. The second task was affective perspective-taking task. This task also had a series of pictures shown to the participants, half of the pictures showed the character showing an inappropriate expression to the situation and other half of the pictures showing the appropriate emotions. The participants were shown the pictures and asked about the character's emotions, and how well they perceived someone else's emotions other than their own was measured. Results showed that while there was no difference in performance between the monolinguals and the bilinguals in the cognitive perspective task, bilinguals were better at affective perspective-taking task than the monolingual children, thus showing that their affective perspective-taking ability was better than those of the monolinguals.

L. Fan et al. (2018) investigated the emotion activation of bilinguals in their two languages and the extent of automaticity of the activation. To examine this, late Chinese-English bilinguals performed face-word emotional Stroop task. 20 Chinese facial pictures along with 24 emotion words- 12 English, 12 Chinese, within which 6 were of positive valence, and 6 of negative valence. The words were superimposed upon the facial expressions and participants were asked to respond to facial expressions and ignore the emotion word imposed on the picture. It was found that RTs for incongruent conditions were longer than for congruent conditions. The response was slower in L2 as compared to L1, and there was a greater Stroop interference effect while performing in the dominant language.

Sari et al. (2019) investigated bilingual, bicultural adolescents to see how their language usage relates to their affective well-being, in Indonesia, a non-Western multilingual, multicultural context. Bilingual adolescents from three different ethnic groups participated in the study three groups of Javanese, Toraja, and Chinese, who all also spoke Bahasa Indonesia, the lingua franca. Javanese and Toraja are minority indigenous ethnic group descendants, and Chinese are minority immigrant descendants. Methodology included Bahasa Indonesia and ethnic language usage at home questionnaire, Bahasa Indonesia and Ethnic language in public area usage which is a part of LEAP-Q (Marian et al., 2007) and a Picture naming test (PNT). Affective well-being was measured using the Positive and Negative Affective Schedule (Watson et al., 1988).Results showed that while all groups used Bahasa Indonesia similarly in a public setting, the similarity in ethnic language usage was found only among Javanese and Toraja groups. There also was a positive relation between affective well-being and proficiency in Bahasa Indonesia in dominant and non-dominant ethnic groups. While national language usage was shown to be positively associated with affective well-being, there was no such relation between ethnic language usage and affective well-being.

A study by Basnight-Brown et al. (2022) examined the emotion processing mechanisms of highly proficient multilinguals in each of their L2 and their L3 in this qualitative and quantitative study. The participants were university students from Kenya, Tanzania, and Rwanda with a knowledge of minimum three languages. The L1 varied across the participants whereas their L2 and L3 were Kiswahili and English, with their English skills rated higher and more frequently used during the day. The first part of the study was norming study where they were given a list of emotion words and emotion-laden words which they were asked to translate to Kiswahili without using any help. The second part was an affective Simon task. Emotion words and emotion-laden words were presented one by one on the screen, in both Kiswahili and English. If the word was written in white text, then they had to respond to the meaning of the word (positive/negative), if the text was any other colour, they had to respond to the colour of the text. The next part of the study was qualitative, and the participants had to write an essay on their language experiences, specially how and when they use their multiple languages. The results from this study aligned with the premise of previous studies that negative emotions are more strongly encoded in one's L1, when the quantitative data results showed significant effects for positive emotion items only, alluding to the possibility that negative emotions as not as strongly encoded in one's L2 and L3. Results from Affection Simon tasks also observed significant effects in positive stimuli only. The qualitative data showed that majority of the multilinguals claimed to use their L1 when expressing negative emotions such as anger or frustration and preferring to switch to their L2 or L3 while discussing positive emotions.

A study by Williams et al. (2020) examined the relationship between code-switching and emotional facial expressions of bilingual children, parents and their teachers. All participants involved in this longitudinal study had Chinese as their L1 and English as their L2. The study consisted of observing the behaviour of chid and parent, as well as their interactions as they completed a parent-child puzzle box, to observe the range of the facial emotions of parent, both positive and negative, while interacting with their child. Results of this observational study showed that when showing more positive facial emotion, parents code-switched less frequently, as compared to when they showed a more negative facial emotion. However, code-switching did not seem to predict any changes in facial emotion behaviour. The intensity of parent's negative facial emotion predicted the frequency of subsequent code-switching; however, this was not seen in case of positive facial emotion. They tended to code-switch more after a negative facial emotion such as anger or frustration and code-switch less after displaying a positive facial emotion like joy or enthusiasm.

Khoshkhooy et al. (2023) compared performance of monolingual and bilingual elementary school girls in emotional working memory capacity. The monolinguals spoke Persian and the bilingual children spoke Armenian and Persian. The tasks included a children's emotional working memory capacity test, and number capacity test (reading forward and reverse digits). Results showed that bilinguals had better emotional working memory capacity and emotional cognition function. Another study that explored emotional working memory capacity of bilinguals (Ma et al., 2020) compared performances of proficient and non-proficient bilinguals. The participants were Chinese-English university students, whose performance was examined to see if the depth of one's bilingual experience on traditional working memory tasks get transferred on one's emotional working memory. The first task performed was emotional delay-matching-to-sample task where 4 groups of numbers were shown one after another with emotion faces on either side of the number. The task was to see if the number on the screen has appeared in the previous four sets of numbers. The emotion faces displayed were either neutral faces, positive (happy) faces, and negative (sad/angry/fear) faces. Results showed that in neutral emotion condition, proficient bilinguals showed better performance than non-proficient bilinguals, with shorter response timings and higher accuracy. Proficient bilinguals also performed better in emotion face condition with shorter response timings. The proficient bilinguals also showed an advantage effect, but only in high memory load conditions (three or four digits), and not in low memory load conditions (memory load of two digits). The second task was an emotional n-back task, where letters were shown one by one, with emotion faces on either side of the stimulus. The task was to judge if the letter on the screen was same as the letter they saw one screen before (1-back) or 2 screens before (2-back). Results in this task were similar to the previous task. Proficient bilinguals had shorter response timing than non-proficient bilinguals in neutral emotion condition as well as emotion conditions, both positive and negative emotions. Interestingly, the difference in response timing between proficient and non-proficient bilinguals was significantly greater in 2-back task than in 1-back task, showing that as the task became more complex, the difference in performance between the proficient and non-proficient bilinguals became more pronounced.

To investigate bilingual language control in emotional contexts, Jiang et al. (2024) looked at the interaction of one's emotional state with their language switching habits. Using the premise of the Adaptive Control Hypothesis (Green & Abutalebi, 2013) to define the language switching patterns commonly used in picture naming tasks, they claimed that voluntary language switching resembled the mechanism of Dense Code-switching Context, whereas cued-language switching was more similar to Dual Language Context. They proposed that the effect of one's negative emotional state would be more prominent in voluntary language switching performance than in cued language switching performance. Two groups of Chinese-English bilingual university students were made to perform picture naming task- one group performed voluntary picture naming task, where they could freely choose the language in which to name the stimulus on the screen, and the other group performed the cued picture naming task, where the participants had to name the picture in the language specified depending on the cue (blue or red square) presented before the stimulus appeared on the screen. The assumption was that negative state would induce greater code-switching, slower responses, greater switching and mixing costs as compared to neutral emotion state, whereas, positive emotion state would elicit less frequent code-switching, faster responses, smaller switching and mixing costs compared to neutral state. Results showed that positive state prompted faster overall RTs, and negative state prompted slower overall RTs. There was a marginally significantly larger voluntary switching cost seen in frequent code-switchers but smaller voluntary switching cost seen in infrequent code-switchers.

*Neurological studies.* Jończyk et al. (2016) examined differences between processing a bilingual's languages when it comes to affective content through electrophysiological data. English monolinguals and Polish-English late bilinguals took part in this study. The task was to decide if the sentence on the screen was made sense upon reading the final word. The monolinguals had to respond to only English sentences, the bilinguals had to respond to both Polish and English sentences. Results showed a strong difference in N400 modulation between affective valence in L1 and affective valence in L2. Negative English sentences caused reduced N400 amplitudes compared to positive English sentences, positive Polish sentences, and negative Polish sentences, thus leading it to be supposed that perhaps negative content might be getting suppressed when it is expressed in L2.

Another study (Toivo & Scheepers, 2019) also tested this claim by measuring pupil dilation of late bilinguals in response to high arousing and low arousing words in the participants' first and second language. The participants were German-English and Finnish-English late bilingual university students, monolingual native English speakers were used as control group. The task was a linguistic decision task where the participants were asked if they recognised the word presented on the screen and its meaning. The words were filler words, high arousal and low arousal words. Results showed that for the German and Finnish bilingual groups, if the stimuli were presented in their L1, a significant effect of the word type was found on pupillary responses. However, when the bilinguals were presented with the stimulus in their L2 (English), there was no effect of the word type on the size of the pupils. While high-arousing words in English did evoke more dilated pupils than low-arousing words, this effect was found only in participants whose L1 was English. These findings, thus, sided with the reduced emotional resonance in L2.

Naranowicz et al. (2022) observed Polish-English unbalanced bilinguals, and how their moods affected their lexico-semantic processing, while recording their electroencephalographic (EEG) activity. Two sessions were conducted a week apart, each session involving positive or negative mood induction. Participants were made to watch silent film clips to induce the targeted mood and then made to perform a semantic decision task. The semantic decision had the participants decide if the sentence displayed was meaningless or meaningful. Results showed that there was a reduced N1 in the negative mood as compared to positive mood in L2 scenario, a reduced N2 in negative mood as compared to positive mood in L1 scenario. A reduced N400 was found when comparing meaningless sentences to meaningful sentences in L1, when in positive mood. Thus, these findings suggest that moods, positive or negative, affect lexico-semantic decision and processing differently in L1 and L2.

In their study, H. Liu et al. (2023) investigated the neural and behavioural activity of bilinguals by observing the influence of processing emotion-laden words on their language switching performance. The participants were Chinese-English bilinguals and the task performed was an emotional judgement task. In this task, an auditory stimulus was presented to which the participant had to vocally respond "positive" or "negative" depending upon its emotional valence in the same language as the auditory stimulus. This was then followed by a picture naming trial where the participant had to name the stimulus on the screen in L1 or L2 depending on the language cue. The neural activity was recorded using an fMRI. Results from behavioural data showed that there were slower responses in switch trials as compared to non-switch trials when the bilinguals were picture naming after processing positive words, demonstrating a larger switch cost. In comparison, this switch cost was near negligible while naming pictures after processing negative words. Neural data revealed that comparing performance between switch and non-switch trials, switch trials showed increased neural activation while processing positive-laden words and processing of negative-laden words showed reduced neural activations. These activations were found in highly overlapping neural network, including the left SMA, left TPOsup, right fusiform, left cerebellum, and vermis. These brain regions have shown activation during cognitive control, language processing, and emotional processing.

## 2.4 Research Gaps

This section lists some gaps in the existing literature with potential to inform the current research work.

*Mixed results.* The studies reviewed above do not all show a significant positive relationship between bilingualism and executive control. While many studies have shown a positive relationship, some studies have shown mixed results, where the positive relationship might be seen in some aspects but not all (C. Barbu et al., 2018; Blom et al., 2017; Calabria et al., 2011; Champoux-Larsson & Dylman, 2021; J. Chen et al., 2023b; Gosselin & Sabourin, 2023; X. Han et al., 2022; Hartanto & Yang, 2016, 2020; Kałamała, Ociepka, et al., 2020; Lai & O'Brien, 2020; Ng & Yang, 2022; Paap et al., 2021; Pot et al., 2018; Yang et al., 2023) or no performance differences have been found between the different groups (Johann et al., 2022; Morton & Harper, 2007).

This calls for the need for continuous rigorous exploration in this domain to try and come to a definite conclusion about the presence of bilingual advantage and what factors help influence its activation.

*WEIRD studies.* This study has reviewed studies from WEIRD (C. Barbu et al., 2018; Beatty-Martínez et al., 2019; Blom et al., 2017; Calabria et al., 2011; Carter et al., 2023; Gosselin & Sabourin, 2023; Johann et al., 2022; Jończyk et al., 2016; Kałamała, Szewczyk, et al., 2020; Luk & Bialystok, 2013; Morton & Harper, 2007; Naranowicz et al., 2022; Nour et al., 2020; Paap et al., 2021; Poarch, 2018; Pot et al., 2018; Segal et al., 2019; Soveri et al., 2011; Struys et al., 2019; Timmer et al., 2017; Toivo & Scheepers, 2019; Weissberger et al., 2015) as well as non-WEIRD (Basnight-Brown et al., 2022; J. Chen et al., 2023b; L. Fan et al., 2018; S. Han & Lee, 2013; X. Han et al., 2022, 2023; Hartanto & Yang, 2016, 2020; Karimi & Hosseini Rad, 2021; Kheder & Kaan, 2021; Khoshkhooy et al., 2023; Lai & O'Brien, 2020; S. Li et al., 2021; H. Liu et al., 2023; Madrazo & Bernardo, 2020; Ng & Yang, 2022; Rafeekh & Mishra, 2021; Sari et al., 2019; Yang et al., 2023; Yuan et al., 2021) background. Some studies also compared performances of participants coming from WEIRD and non-WEIRD background (Alrwaita et al., 2024; Ooi et al., 2018; Tao et al., 2015).

As seen above, over the years, there has been an increase in studies published from non-WEIRD population, helping bring to the forefront the rich linguistic background of countries such as Algeria (Kheder & Kaan, 2021), India (Rafeekh & Mishra, 2021), Indonesia (Sari et al., 2019), Iran (Khoshkhooy et al., 2023), Philippines (Madrazo & Bernardo, 2020), Sub-Saharan Africa (Basnight-Brown et al., 2022), etc. These are, but a few studies that have just begun to scratch the surface of the bilingual experience and the contribution that non-WEIRD studies can make in this domain will significantly add to the understanding of the complexity of being bilingual.

## 2.5 Chapter summary

This chapter provides a review of the state of the art in studies examining relationship between bilingualism and executive control. This literature survey has examined bilingualism studies examining children, young adults, and adults. It has seen studies compare monolinguals and bilinguals, as well as comparative studies done among bilinguals.

This chapter then looked at studies that explored the bilingual variable of language switching and interactional context in relation with executive control, and then few other bilingual features such as second language proficiency, diglossia, presence of interlocuter, etc. Then this chapter briefly elaborated on some studies that have explored the neurological domain of bilingualism and executive control be it through electrophysiological (EEG) measures, fMRI, pupillometry, etc. This chapter then also surveyed papers that have researched the domain of bilingualism and affective control.

Upon examining the research done in this domain, it is clear that this is not an exhausted field, with more studies coming up within the last few years, trying to explore the minutiae of bilingualism to better understand this phenomenon. Even with the steady flow of research in this domain, there have been studies with mixed results. That, along with the increasing number of studies coming from the non-WEIRD population, it is clear that this study's attempt to unravel the mystery of bilingual advantage will not be in vain.

# 3 Methodology

## 3.1 Introduction

The backbone of any research is its methodology; stimuli, tasks, tools, participants and data analysis are the main components of this. Psycholinguistic research, being an empirical science, is dependent on task-based data collection method. Research in psycholinguistics aims to unravel the relationship between language and the human mind, in terms of its correlation with other mental functions. Hence, the methods used in this field of inquiry are designed to explore the cognitive processes underlying language use and these methods include computational modelling, neuroimaging techniques, behavioural experiments and so on. The fundamental motivation behind experimental studies is to understand or establish a relationship between the variables that are to be studied, namely the dependent and independent variables. The variables manipulated by the experimenter are the independent variables, and the variables expected to be influenced by the changes in the independent variables are called dependent variables. Based on the aims and objectives of the study, the independent variables are chosen and through the relationship between the independent and dependent variables, the researcher is able to establish whether the relationship is causal or conditional, etc (Vorwerg, 2012).

The focus of the current study is to explore a number of cognitive processes in general, and cognitive control mechanisms in particular, in terms of their interaction with bilingualism. In so doing, this study makes use of several standard experimental protocols from the field. All the experiments are behavioural measures and aimed to investigate how proficient bilinguals navigate various cognitive control tasks and thereby show their interaction with bilingual practices through variable reaction times (RTs).

The study included experiments using tasks such as Simon task, *N*-Back task, task-switching, Stroop task, etc. Along with the experimental design, questionnaires were also used for collecting background information of the participants. The questionnaires gave a comprehensive understanding of the linguistic profiles of the participants whereas the tasks that the participants performed were used to assess their cognitive control mechanisms. Data analysis was done using the software package R. This chapter discusses each of the tools and methods of data collection and analysis in detail.

## 3.2 Chapter overview

This chapter details the methodology employed in conducting the present research work, specifically the various tools and methods which have helped operationalise this research to answer the research questions systematically. This study has performed 5 experiments, for which 4 questionnaires and 8 tasks were utilised. Given below is a detailed description of the participants, the questionnaires used, and the tasks performed, the tools used to create the tasks, and the purpose behind using each methodology.

## 3.3 Participants

A total of 231 participants took part in the study. They were all students of Indian Institute of Technology, Guwahati. All the participants were within the age range of 18-35 years, hailing from various parts of India. All participants were bilinguals with English as their L2. The L1 varied across participants. Hindi was the other common language to all of them, along with English. First languages of the participants included, though are not limited to, Assamese, Awadhi, Bangla, Bhojpuri, Bhojpuri, Boro, Harayanvi, Kannada, Kuki, Magahi, Malayalam, Marathi, Marwadi, Meitei, Mizo, Odia, Pahadi, Punjabi, Rajastani, Tamil, Telugu, Tulu, Vaiphei, etc. Since the experiments did not involve linguistic tasks, the varying L1 across participants was not considered as a problem.

Table 3.1 below gives a brief description of the task, the number of participants, and their age range.

| Experiment (Chapter) | Task | No of participants | Age range |
|---|---|---|---|
| Experiment 1 (Chapter 4) | Bivalent Switching Task (Number) | 63 | 18-25 |
| Experiment 2 (Chapter 4) | Univalent Switching Task | 61 | 18-35 |
| Experiment 2 (Chapter 4) | Bivalent Switching Task (Shape) | 61 | 18-35 |
| Experiment 3 (Chapter 5) | N-Back Task | 61 | 18-35 |
| Experiment 4 (Chapter 6) | Simon Task | 61 | 18-35 |
| Experiment 4 (Chapter 6) | Classic Stroop Task | 107 | 18-25 |
| Experiment 4 (Chapter 6) | Classic Go/No-go Task | 107 | 18-25 |
| Experiment 5 (Chapter 7) | Emotion Stroop Task | 107 | 18-25 |
| Experiment 5 (Chapter 7) | Emotion Go/No-go Task | 107 | 18-25 |

*Table 3.3.1: Brief description of tasks, participants and their age range.*

## 3.4 Questionnaires

This study used 4 questionnaires to collect linguistic data of the participants, to examine their language history, focusing on their language switching habits *(see Appendices B, C, and D)*. The questionnaires used for the same are based on the questionnaires commonly used by various studies. They are discussed briefly as follows.

### 3.4.1 LEAP-Q

The Language and Proficiency Questionnaire, this is a questionnaire tool for collecting self-reported background information on bilingual and multilingual speakers. It was developed by Northwestern Bilingualism and Psycholinguistics Research Lab, and was first introduced in a paper published in the Journal of Speech, Language & Hearing Research (Marian et al., 2007).

This questionnaire was designed to collect broad as well as specific measures of language usage. For all the measurable components of the questionnaire that enquired about degree and strength of language proficiency, a 10-point Likert scale (0-10) was used. The broad measures included language dominance, language exposure, and language preference. The specific measures consisted of ages of acquisition, ages of attaining fluency, length of immersion in different contexts, estimates of proficiency in speaking, reading, and understanding, ratings of how different contexts contribute to the acquisition of the language, extent of exposure to the language in different contexts, degree of accent, etc for each of the language known by the participants.

This questionnaire is used by researchers to provide comprehensive descriptions about the bilingual participants and based on their responses, helps in dividing them into groups and sub-groups for various purposes such as checking language proficiency levels, confirming native-speaker status, documenting differences in linguistic abilities between their various languages, etc.

The current study modified the LEAP-Q to better suit the bilingual linguistic scenario of India, as well as for the purpose of focusing on the research questions put forward. Questions related to language acquisition and language proficiency were therefore either edited or omitted, and more focus was on questions that delved into the participants language usage in various contexts, and their language switching habits. These included questions that looked at language usage of the participants in their day-to-day lives. This questionnaire was used for Experiments 1 (Chapter 4), 2 (Chapter 4), and 3 (Chapter 5) to get a look at participants' daily language usage experience.

### 3.4.2 BSWQ

Developed by (Rodriguez-Fornells et al., 2012), the Bilingual Switching Questionnaire (BSWQ) is a psychometric measure that is used to characterize individual differences in language switching. It consisted of 12 questions, 11 of the questions were yes/no questions, and one question was a rating question. This questionnaire was formulated for Spanish-Catalan bilingual speakers;

therefore, the questions in the original questionnaire specifically investigated the language switching of participants between Catalan and Spanish.

For the current study, we made some minor changes, keeping in mind the variety of languages that the participants spoke as well as the varying number of languages they spoke; some of the questions were omitted or edited by removing names of languages, rather keeping it more general. This questionnaire was used in Experiment 4 and Experiment 5 (Chapter 6) to get a detailed, albeit subjective report on bilingual participants' language switching behaviour.

### 3.4.3 LHQ 3

One of the most common questionnaires used in bilingual studies is the Language History Questionnaire (P. Li et al., 2020). The aim of creating this questionnaire was to have a standardized set of questions that can benefit researchers, investigating multiple aspects of bilingualism, in getting information on bilingual participants, their linguistic history and language usage. Keeping this in mind, 41 studies were examined and common questions related to second language and bilingualism research were taken as a base for creating the first version of the questionnaire (P. Li et al., 2006). From the more generic LHQ 1, the LHQ 3 (P. Li et al., 2020) evolved, factoring in the feedback and requests of the users.

For this study, only those questions pertaining to the participants' daily bilingual language usage were taken and edited to suit the context of the participants' linguistic environment.

### 3.4.4 Language Switching Frequency Questionnaire

The first version (Hartanto & Yang, 2016) had a 5-point Likert scale to report regarding the extent to which they used their 2 languages within the same context or different contexts. This initial questionnaire had only 2-way division between Single Language Context (SLC) and Dual Language Context (DLC). The questionnaire asked the participants their language switching habits in various contexts such as home, school, work and other scenarios. Based on their scoring, the participants were divided into the two groups.

A revised version, renamed as the *Interactional Contexts Questionnaire,* was published in 2020 (Hartanto & Yang, 2020). This version had 5 questions in total. First, asking the percentage of time the participants spend each at home, school, work and other scenarios. Then, the next 4 questions asked the participants' language switching frequency in each of the 4 situations (home, school, etc.). The participants were asked to measure, in percentage, if they speak in one language and rarely switch (Single Language Context); if they speak different languages with different speakers, while not mixing languages in one utterance (Dual Language Context); or if they routinely mix languages within an utterance (Dense Code-Switching Context)- in each of the 4 situations. Each of the situations broadly mimicked the three different language usage contexts. The scores the participants gave were then calculated to estimate each participants' preference of each interactional context by using the following formulae:

Single Language Context (SLC) index =

$$\sum_{i=4}^{4} \frac{p_i \times sl_i}{100}$$

where $p_i$ is the amount of time spent in each situation (home, school, work, others); $sl_i$ is the percentage of SLC in each given situation.

Similarly, for Dual Language Context (DLC) index =

$$\sum_{i=4}^{4} \frac{p_i \times dl_i}{100}$$

where $dl_i$ is the percentage of DLC in each of the 4 situations.

Finally, for Dense Code-Switching Context (DCS) =

$$\sum_{i=4}^{4} \frac{p_i \times dc_i}{100}$$

where $dc_i$ is the percentage of DCS for each participant in each situation. Each of these indices for each of the participant gives a score and whichever group they show the highest score, the participants are categorised into that language context group. The revised version included the third interactional context of Dense Code-Switching context along with SLC and DLC.

This study kept the questionnaire and its methodology intact and just edited the environment of language usage from Home, School, Work and Places other than Home, School, Work to Home, School, Social and Non-social environment, since the participants were all students. Participants were categorized as belonging to one of the three groups based on whichever index got the highest score, calculating from the score the participants got for each index.

## 3.5 Tools

### *Stimulus presentation*

All the experiments were designed on Windows 10 operating system, using the experiment building software E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA). E-Prime is a software designed by Psychology Software Tools, Inc., for stimulus presentation and behavioural data collection. It is one of the most preferred software for experiment designing and data collection (Alrwaita et al., 2024; Gade et al., 2024; X. Han et al., 2023; H. Liu et al., 2023; Yang et al., 2023).

For data collected offline, the experiment was presented on a Dell laptop with a 13.3-inch viewing screen. The participants sat, individually, in a quiet, peaceful environment with the screen at a comfortable viewing distance. They were presented with verbal instructions before beginning the task. For the data collected during COVID lockdown *(see Chapter 4)*, data was remotely collected through an online version of E-Prime known as E-Prime Go (Psychology Software Tools, Pittsburgh, PA). Link to the task was emailed to participants, who were then redirected to the task, the responses to which were uploaded to the researcher's E-Prime Go account.

### *Recording the responses*

The responses to almost all the tasks performed were recorded on the keyboard of the laptop in use, except for the Classic and Emotion Stroop task, which was recorded using Chronos, a stimulus and response device. It is a USB based instrument by Psychology Software Tools, which can be attached using to the desktop or any stimulus presentation device to record participants' responses. The device consists of 5 keys, whose responses can be customised according to the task requirement. Figure 3.1 shows an image of Chronos, the response collecting device.

*Figure 3.5.1: Chronos device used for response recording.*
*(Source: https://pstnet.com/products/chronos/)*

## 3.6 General Procedure

The participants in each task, including those who performed the task remotely, were asked to sit individually in a quiet space with no distractions. They were first given verbal instructions on how the task would go after which they were made to sit and perform the task.

## 3.7 Tasks

There are several behavioural tasks that are used to study executive control functions. The current study used 8 such standard tasks, namely: Switching Tasks (Univalent and Bivalent), N-Back Task, Simon Task, Classic Stroop Task, Emotion Stroop Task, Classic Go/No-go Task, Emotion Go/No-go task. Each of the tasks are discussed below.

### 3.7.1 Switching Task

Over the past many years, Switching Tasks have been used to study the executive control processes (Allport et al., 1994; Jersild, 1927; Rogers & Monsell, 1995). These tasks usually require participants to perform two different kinds of tasks one after another. Studies on switching between tasks provide an insight into the complex processes that are involved in dissociating from one task and then switching to a new task. Participants are shown a series of stimuli upon which they must perform certain tasks, the order of whose occurrence which may change periodically. Studies investigate the performance difference in Reaction Time (RT) which is seen to be slower for trials in which there is alternation of tasks as compared to trials where there is repetition of tasks. This difference between repetition and alternation is known as switch cost.

Based on the sequence of task presentation, the trials of a task can either be a repeat trial or a switch trial. A trial is a repeat trial if the task to be performed is same as the previous trial, whereas a trial is a switch trial if the task in the current trial is different from the previous trial. In a switching task, the trials are grouped into task blocks based on the sequence of their occurrence. In a Pure block, for instance, one task (A) occurs repeatedly for multiple trials followed by multiple trials of the other task (B). In Alternate block, tasks may occur in ABAB manner (one trial of Task A followed by one trial of Task B), or even AABB sequence (two trials of Task A, followed by two trials of Task B). Another block type is the Mixed block where the tasks appear in a random order.

The difference in the performance in the RTs in switch trials and repeat trials within the Mixed task block is known as switch cost or Local switch cost (Strobach et al., 2012). Another type of switch cost is the Mixing Cost. Also known as Global Switch Cost, it is the difference in the performance of Repeat trials in Pure task block and Mixed task block.

Based on the stimulus-response mapping, switching tasks can be of two types: Univalent Switching Task, and Bivalent Switching Task.

#### 3.7.1.1 Univalent Switching Task

In a Univalent Switching Task, the tasks to be performed are completely different from one another, with different sets of stimuli for each task. The response keys assigned to each task also have no overlap. Each stimulus, therefore, is uniquely associated with one task, one response. Figure 3.2 below shows a schematic representation of how a typical Univalent Switching Task proceeds. The participant has to perform either Task A or Task B. The stimulus displayed for Task A (Stimulus A) is completely different from that of Task B (Stimulus B), and both of their corresponding response also have no overlap, Response A for Stimulus A shown for Task A and Response B for Stimulus B shown for Task B.

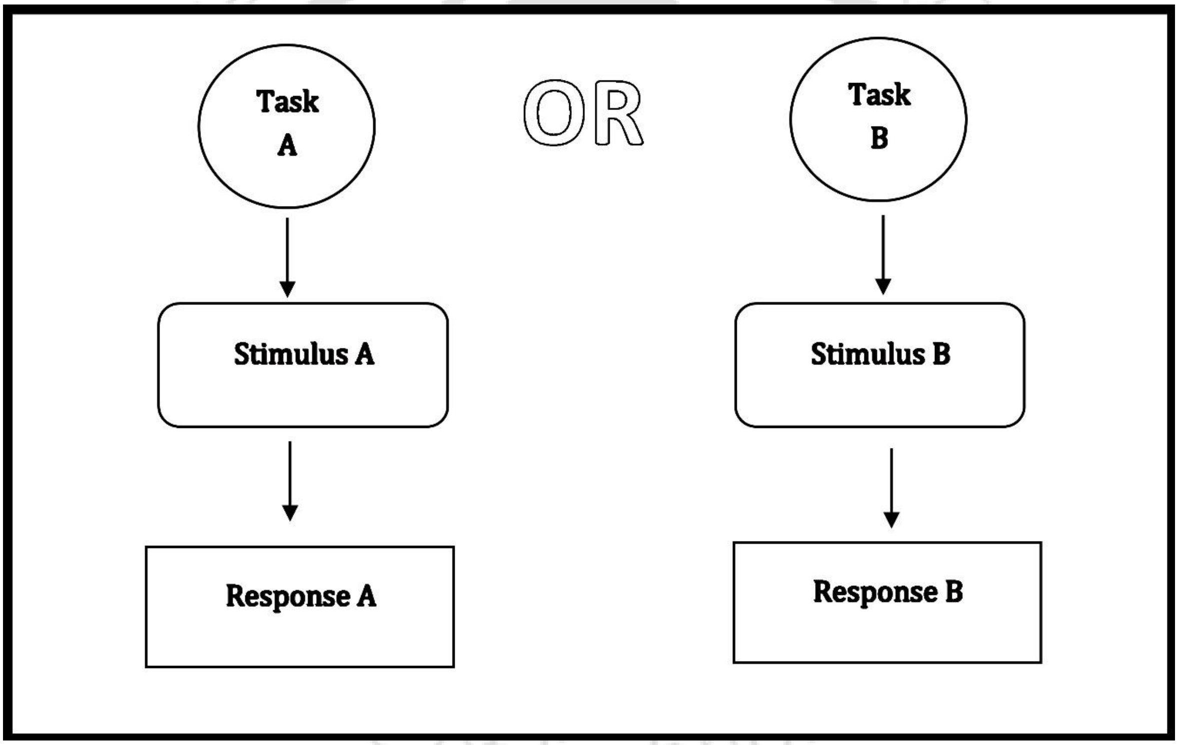


*Figure 3.7.1: Schematic diagram of a Univalent Switching Task.*

A common example of a univalent switching task, which was also used for this study, is the Number-Letter task. Adapted from Rogers & Monsell (1995), this task presents the stimulus as either a letter or a number. If it is a number, then the participant has to perform a number related task, for instance, 'categorise the number on the screen as odd or even'. If the cue is a letter, then the task is alphabet related, like 'categorising it as a consonant or vowel'. Some studies present the cue before the stimulus, and present both the number and letter at once (Brown et al., 2007), or if the number-letter pair was positioned in the top two quadrants of the screen, it was a Numbers task (odd/even), and if the number-letter pair was presented in the bottom two quadrant of the screen, it was a Letters task (consonant/vowel) (Y. Q. Chen & Hsieh, 2018; Miyake et al., 2000; Snyder et al., 2021).

Studies on bilingualism have used the task switching paradigm to observe the performance of participants in various executive functions. Very few studies, however, use univalent switching task to examine the same, for instance, (Jylkkä et al., 2021; Sörman et al., 2019; Soveri et al., 2011; Yow & Li, 2015), and instead preferring bivalent switching task (X. Han et al., 2022; Hartanto & Yang, 2016, 2020; Khodos et al., 2021; Prior & Macwhinney, 2010).

#### 3.7.1.2 Bivalent Switching Task

The bivalent task consists of a single set of stimuli upon which 2 different kinds of tasks need to be performed. The task to be performed is determined by the cue which corresponds to the task. The response to both the tasks requires the same set of response keys. Therefore, in a bivalent task, the stimulus and the response keys remain the same, while the different cues determine which task is required to be performed. Figure 3.3 gives a generalised schematic model to show how a typical bivalent switching task would be performed. The stimulus presented for both the Task A and Task B is same, the cue, often presented before the stimulus is what determines which task is to be performed. Therefore, there is an overlap in the stimulus and the response keys, the tasks are differentiated based on the cue presented.

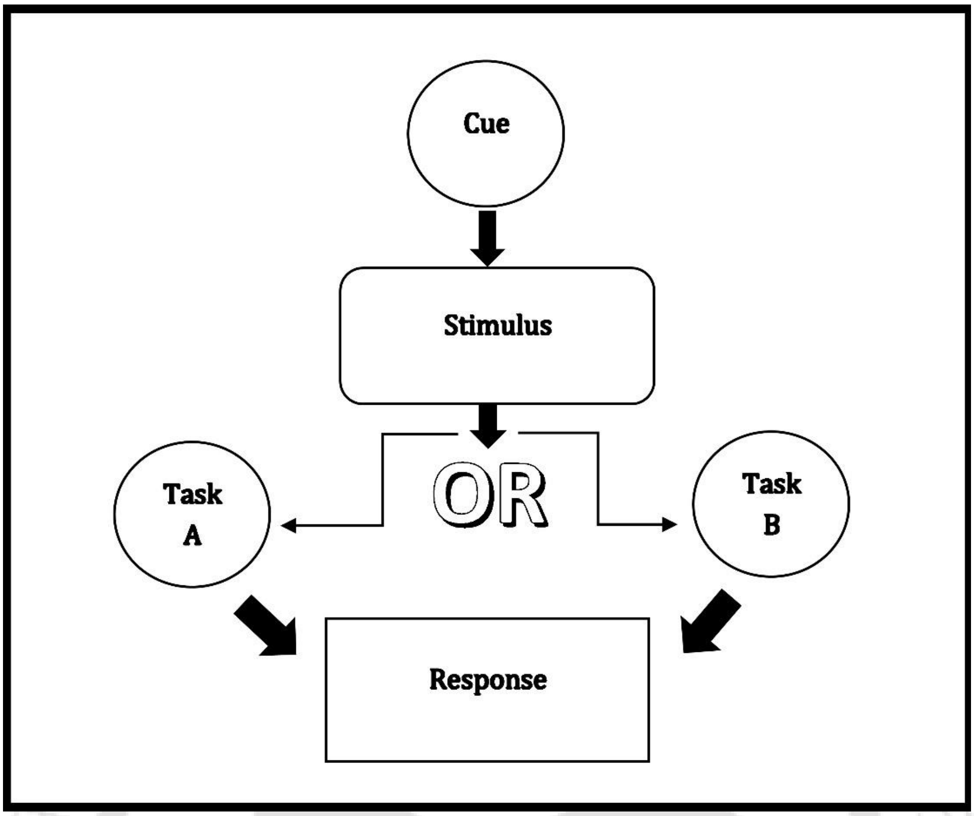


*Figure 3.7.2: Schematic diagram of a Bivalent Switching Task.*

Some common examples of bivalent switching task are the Shape/Colour Task and Parity/Magnitude Numbers Task. In a Shape/Colour task, a figure is presented on the screen, and depending upon the cue the participant had to either categorize it based on shape or colour. In Parity/Magnitude task a number is displayed on the screen and the participants has to either decide if the number was odd or even (Parity task) or greater than or lesser than a specified number (Magnitude task).

Over the years, various studies have examined the effect that bilingualism might have on bivalent task switching performance (Hernández et al., 2013; Johann et al., 2022; Mas-Herrero et al., 2021; Prior & Macwhinney, 2010; Sörman et al., 2019) by comparing the performance of bilinguals with monolinguals, with bilinguals performing better than the monolinguals on various factors such as having smaller switching cost and having faster performance in most studies.

### 3.7.2 *N*-back Task

This is a common task often used to assess working memory, and to also improve the working memory capacity. It was first introduced by Wayne Kirchner in 1958 (Kirchner, 1958); in this task the participants are presented with a sequence of stimuli. The task is to indicate if the stimuli currently on the screen is the same as the stimuli shown '*n*' sequences ago. So, for instance, in 1-

back task, the stimulus on the screen is considered a target if it is the same as the stimulus presented 1 stimulus ago. If it is not same, then it is a non-target. Similarly, in a 2-back task, the stimulus on the screen is a target stimulus if it is the same as the stimulus presented 2 stimuli ago. In a 0-back task, a stimulus is picked as a target (for instance 'X') and every time it appears on the screen, the participants have to respond accordingly. In his seminal paper, Kirchner (1958) examined the effects age had on short-term memory retention. He had his participants perform four variations of the *n*-back task, 0-back, 1-back, 2-back and 3-back task.

The stimulus presented can be auditory or visual in nature. In an auditory *n*-back task, participants are made to listen to an auditory stimulus- it could be a digit, or a syllable (Gonçalves & Mansur, 2009), or a consonant (Rovetti et al., 2021). The visual stimulus presentation is a more commonly used version of the *n*-back task used to test the working memory capacity.

Most studies report reaction times (time taken for the participant to respond to a stimulus) as well as errors. It has generally been reported that as the *n*'s increase, the reaction times also tend to increase and the accuracy tends to decrease (del Angel et al., 2015; Gajewski et al., 2018; Kane et al., 2007; Meule, 2017). Studies examining the working memory function of the cognitive control among bilinguals have also used this task to measure the same (Johann et al., 2022; Soveri et al., 2011; Yow & Li, 2015). In the current study, the *N*-Back task is used to measure the working memory performance of the young adult bilinguals, and compare if their contextual language usage had any effect on their performance of the task.

### 3.7.3 Simon Task

This is a task often used as a measure for inhibitory control function. This task was named after J.R Simon from their study (Simon & Rudell, 1967). This first version of this task was an auditory stimulus-response task. The participant had to respond to the word presented in each ear, one at a time, and respond to the word accordingly. So, if the word they heard was 'right' they had to press the right-hand key, and if the word they heard was 'left', the participants had to press the left-hand key.

It was found that the response was faster when the stimulus heard corresponded to the ear it was presented in (for instance, hearing 'right' in the right ear) as compared to when the stimulus presented and the ear it was presented in were opposite (like hearing 'right' in the left ear). This was known as the Simon effect. The purpose of this task was to see if the participants could inhibit their response to a task-irrelevant cue and focus instead on task relevant cues.

Recent studies however have adapted this task to the visual platform. The stimuli presented might vary, but the task remains the same. When the stimulus is presented on the screen, the participants have to ignore the placement of the stimulus and just respond with the response corresponding to each stimulus. Such tasks often occur in three conditions, namely Neutral, Congruent, and Incongruent conditions. In neutral condition the stimulus is at a neutral position, usually at the centre of the screen. In congruent condition the position of the stimulus and the response is on the same side. In incongruent condition, the position of the stimulus is on the opposite side as the response corresponding to it. The difference in performance in congruent and incongruent conditions is known as the Simon effect.

Studies on bilingualism have often used the Simon task to measure inhibitory control. These studies have ranged from comparing monolinguals and bilinguals of various language groups (Bialystok, Craik, et al., 2005; Bialystok, Klein, et al., 2004; Champoux-Larsson & Dylman, 2021; Morton & Harper, 2007; Sörman et al., 2019), or even among bilinguals (Jylkkä et al., 2021; Soveri et al., 2011; Struys et al., 2019). In this study, the Simon task was used to measure the inhibitory control performance of the bilingual participants, and see if their interactional language usage can determine the inhibitory control performance.

### 3.7.4 Stroop Task

The premise of this task is that a word is presented on the screen. The participants have to ignore the word and instead focus on, and respond to, the colour of the word. First introduced in 1935, (Stroop, 1935), the task involved conflicting stimuli, where the participants had to inhibit their response to one stimulus and instead focus on the less prominent response. The stimuli were colour words written in various colours. For example, 'RED' written in green ink. The participants had to ignore the word and respond to the colour of the text. It was found that the time taken for participants to name the colour when it was written in a different colour ink took longer than when the word written was in the same colour as what the word said, or if the stimulus were just blocks of colour. This difference in response was termed as Stroop effect.

In a typical Stroop colour and word task, the stimuli can appear in different conditions. In a congruent condition, both the colour word and the ink it is written in are same, for example 'RED' written in red ink. In an incongruent condition, the colour word is written in a different colour, like 'RED' written in green. The difference in performance between congruent and incongruent conditions is called Stroop effect. This task is based on the rationale that reading is an automatic process whereas naming the colour of words is not. Thus, asking participants to name the colour and ignore the 'word' creates a conflict.

This task investigates the conflict monitoring and conflict resolution abilities among the participants. In the current study, this task was used with bilingual participants to investigate the difference in Stroop effect as a possible outcome of the difference in bilingual language switching context.

#### 3.7.4.1 Neutral Stroop Task

The traditional Stroop task is also known as the neutral Stroop task for its role in investigating non-emotion related cognitive features of the human brain. Bilingual studies have used the Stroop task to examine effect of language interference (Ning, 2021; Šaban & Schmidt, 2021; Suarez et al., 2014; Sumiya & Healy, 2004; Yahya & Özkan, 2022), but also to examine domain general cognitive control performances (Esposito et al., 2013; Sörman et al., 2019; Tse & Altarriba, 2012; Yow & Li, 2015).

#### 3.7.4.2 Emotional Stroop Task

Over the years, the Stroop task and other such tasks have undergone modifications to suit the requirements of the research question at hand. An interesting modification that these psychological measures have undergone is adapting them to measure emotion and emotional valence.

A typical emotion Stroop task, therefore, consists of emotion words and neutral words, the participants have to name the colour the words are written in. Studies have found that participants take longer to respond to emotion words than non-emotion words, this is known as Emotional Stroop Effect (Ben-Haim et al., 2016; Dresler et al., 2009).

Various studies have used the emotion Stroop task either using emotion words (Berger & Davelaar, 2015; Kahan & Hely, 2008), emotion words imposed on emotion faces (Agustí et al., 2017; L. Fan et al., 2018; Kar et al., 2018), and even a verbal version where synonyms of 'happy' or 'sad' are spoken with happy or sad prosody (Filippi et al., 2017).

For the current study, emotional Stroop task was used along with neutral Stroop task in order to get a nuanced understanding of the effect of bilingual language use experience on the outcome.

### 3.7.5 Go/No-go Task

Designed to measure response inhibition, this task measures the ability of a participant to withhold from responding. The premise of this task is quite straightforward. Depending on the stimulus on the screen, the participant has to either respond to the stimulus (Go paradigm) or withhold from responding (No-go paradigm). Just as for Stroop task, two versions of this task were performed. There was the neutral version and the emotional version.

#### 3.7.5.1 Neutral Go/No-go Task

This task is not used as commonly as other inhibitory control related tasks. Studies have used this task to do inhibitory control training (Van Royen et al., 2022). The task involves 2 stimuli, the participants have to respond to one stimulus and refrain from responding to the other stimulus. Studies among bilinguals include examining inhibitory control among bilinguals and trilinguals (Madrazo & Bernardo, 2020), bilingual advantage in bilingual children (Johann et al., 2022), and young bilinguals (Jiao et al., 2019; S. Li et al., 2021). Neurological studies included studies in Event Related Potentials (ERPs) of bilinguals (Kałamała, Ociepka, et al., 2020), comparing ERPs of bilinguals and musicians (Moreno et al., 2014), eye-tracking studies on inhibitory control in bilinguals (J. P. Singh & Kar, 2018).

#### 3.7.5.2 Emotional Go/No-go Task

Studies using emotional Go/No-go are fewer in number. This is similar to the neutral version, however, in the emotional version of the task, the stimulus contains an emotion element, for instance, facial expressions denoting emotions, etc. This task is commonly used to test factors such as performance of cognitive control with respect to one's emotional intelligence (Megías et al., 2017; Tottenham et al., 2011), one's emotion processing, (Greif & Waring, 2018; Schulz et al., 2007), such as comparing the inhibitory control performance between responding to positive and negative emotional information, etc. Studies have also examined controlling emotional facial expressions (Beringer et al., 2022), and in other fields such as gaming disorder (Y. Chen et al., 2022), alcohol use disorder (Sasaki et al., 2023), paediatric anxiety and depression (Ladouceur et al., 2006).

The current study used both, the neutral and emotion versions of the Go/No Go tasks on the bilingual participants to arrive at a fine-grained understanding of the participants' inhibitory control mechanism and to what extent the same is corelated with their *bilingual experience*.

## 3.8 Stimuli

Various stimuli were used as per the requirements of the tasks at hand. These included alphabets (Univalent Letters/Numbers task), numbers (Univalent Letters/Numbers task, Bivalent Even/Odd task, N-Back task), words (Classic Stroop task, Emotional Stroop task), and images (Bivalent Colour/Shape task, Simon task, Classic Go/No-go task, Emotional Go/No-go task). A detailed description of the same have been mentioned in their respective chapters ahead.

## 3.9 Data

All studies used behavioural tasks and thus measured Response Time (or Reaction Time, RTs) of the performance of the participants. The data were generated by E prime and statistical analysis was performed on this output data for various factors like switch cost, Simon effect, etc. The output data were also corelated with the questionnaire data wherever applicable.

### 3.9.1 Statistical procedures

Data obtained from the participants was compiled and analysis was performed. The data was compiled on Microsoft Excel, after which the analysis was performed on RStudio (R Core Team, 2024) on the RTs of the participants. The response times (correct and incorrect) that were above or below 1.5 times the standard deviation from the mean were removed from further analysis. Then the analysis was broadly done on speed as well as accuracy of their performance.

The RT analysis included Type III ANOVA analysis (using Satterthwaite's method), Post-HOC analysis and Linear Mixed-Model (LMM) analysis. Models for LMM analysis were created using the *lme4* function (Bates et al., 2015) and the *lmerTest* function (Kuznetsova et al., 2017) on RStudio, to analyse the relationship between RT and various fixed factors. Models were created with the aim to examine the effect that independent variables Language switching context (LSC), Condition and Accuracy had on the response timings of the participants, as well as the interaction effect the independent (or fixed effects) variables had on each other. Post-HOC analysis included Estimated Marginal Means (EM Means) analysis and pairwise analysis. The EM Means analysis was done using the *emmeans* package (Lenth, 2024), for the various levels of the fixed factors, as well as the interaction between the various fixed factors. The differences among the various levels was analysed using pairwise comparison analysis.

Since participants were provided with a feedback after every trial for every task, accuracy analysis was also performed to see the effect that the feedback might possibly have. For the accuracy analysis, analysis was done on error and post-error performances. For this analysis, the RTs were scaled for standardising the values and stabilizing the model. The error analysis required the generalised mixed model analysis, and post-error analysis used LMM analysis.

## 3.10 Ethics

All participants gave their informed consent to take part in the study *(see Appendix A)*.

## 3.11 Chapter summary

This chapter described the methodology used in the various studies performed. First, the participants who took part in the study are mentioned. It then gives a detailed description of the various questionnaires used for the studies, followed by the tasks the participants performed, tasks following the standard protocols. Finally, the process of data analysis is described and elaborated upon.

The methodology used in the experiments are all standard practices commonly used in behavioural experiments. They were chosen to address the research objectives and ensure robust and reliable findings. The following chapters will present the results obtained from these methodologies, in order to provide insights into the relationship between language usage practices of young adult bilinguals from a densely bilingual country like India, and their executive control functioning.

# 4 Bilingualism and Task Switching

## 4.1 Introduction

The human cognitive mechanism, when presented with a task, organizes its resources to accomplish the task and formulate the appropriate output. To perform the tasks, executive control processes structure themselves to optimally perform the upcoming task, known as task-set configuration (Monsell et al., 2003; Sakai, 2008). The said executive control processes are often studied through the use of task switching (B. Li et al., 2019; Peng et al., 2018; Rogers & Monsell, 1995; Schliephake et al., 2021; Schmitz & Krämer, 2023; Strobach et al., 2012). The reason is that task switching involves a host of control mechanisms like cognitive flexibility, shifting of attention to the next task, inhibiting previous task sets, goal retrieval (Peng et al., 2018; Schliephake et al., 2021; Schneider & Logan, 2009). It was recorded to be first investigated by Jersild (1927) when he did a set of experiments on school and college going students and found that the better one gets at an activity, the greater the loss when shift takes place to another task. The term 'Task Switching Paradigm' was then coined, which is a cognitive experimental design used to investigate how individuals shift their attention and cognitive resources between different tasks. It aims to study the executive control processes and mechanisms involved in task-switching, including how people manage and adjust their executive control strategies when transitioning from one task to another. Successful performance in such situations require careful selection and maintenance of currently relevant task and the flexibility to update tasks when goals change.

A typical switching task, often comprising of two (sometimes even more) tasks, is broadly divided into task blocks. Each task block is comprised of a certain number of task trials that occur in a specific pattern (Arrington & Logan, 2004). In each of these blocks, a trial can either be a repeat trial or a switch trial, depending on what the task performed was in the previous trial. A repeat trial (or a non-switch trial) will be the same task (say, Task A) as the task that occurred just before. Thus, the pattern of occurrence will be A-A. A switch trial, on the other hand, is a trial in which the current task (Task B) is different from the task performed previously, making the pattern A-B. Different combinations of repeat trials and switch trials make up the various task blocks such as: Pure task block, Alternate task block, and Mixed task block. In a pure task block, the task remains the same throughout the block, for example several trials of only one type of task, forming a pattern A-A-A-A. In an alternate task block, a number of trials of task A will be followed by equal number of trials of task B (for instance, the pattern could be A-B-A-B, or A-A-B-B, etc.). In a Mixed task block, the repeat trials and the switch trials may appear in a randomized manner, where there is no specific pattern of occurrence of the two tasks (for instance, A-A-B-A-B-B-B-A-B-A). The performance difference between the repeat trials in Mixed task block and Pure task block is known as global switch cost or global mixed cost, while the performance difference between the repeat trials and switch trials in Mixed block is known as the local switch cost (Tse & Altarriba, 2015).

A key finding in task switch research is that there is delay in the reaction time (RT) that is recorded when switching to a new task. This delay in RT is known as Switch Cost (Monsell, 2017; Schneider, 2007). Strobach and colleagues (2012) discovered that there were higher RTs and error rates in task switches as compared to task repetitions. This led them to conclude that this switch cost reflected the time taken for the executive functions to reconfigure the task set parameters from the previous task to the current task. They further posited that while continuous repetitions of the tasks in that particular sequence may reduce the switch cost but will not eradicate it entirely. Richter and Yeung (Richter & Yeung, 2012) studied the interaction of memory and executive control. They claimed that switch cost reflected 2 principal factors. First was the demand that was imposed when the cognitive system updates and adopts another 'task set', known as reconfiguration, an active process. The assumption is that the requirement to change tasks on alternations evokes a time-consuming control process instigated by an executive control process, resulting in reconfiguration of the subordinate process that perform the task. Second, the interference from previous active task sets reflecting residual attention to a now irrelevant features of the stimuli. The switch cost reflects a passive interference from memories of past task sets, also known as Task-Set Inertia. This interference occurs on alternations because the previous task set and the associations to it are now no longer appropriate for the current task. However, in repetitions there is no interference because the last task set and its associations are still valid.

The task switching paradigm is often used in bilingual-advantage related research, where the participants need to switch between tasks, which can be verbal or non-verbal. It is considered a reliable measure of executive control mechanism. A parallelism can be drawn between a bilingual's ability to maintain their languages and the control process required for task switching, thus making task switching an excellent mode to emulate the language control processes of bilingual mind and its spillover effect into general executive control process. The interactional context of the bilinguals, single-language, dual-language, and dense code-switching context can be said to mirror the switching task blocks, the pure block, the alternate and the mixed block respectively. Over the years various studies have compared performance of bilinguals in various switching tasks. Their performances have been compared with monolinguals as well as other bilinguals on various factors. Several studies also compared performances among bilinguals based on various factors such as language switching and usage context (Alrwaita et al., 2024; Barbu et al., 2020; X. Han et al., 2022; Hartanto & Yang, 2016, 2020; Jylkkä et al., 2017, 2018, 2021; Neveu et al., 2021; Sanchez-Azanza et al., 2020; Segal et al., 2019; Sörman et al., 2019; Timmer et al., 2019; Timmermeister et al., 2020; Weissberger et al., 2015; Yow & Li, 2015).

The mixed results shown in the studies discussed above indicate that the discussion on this topic is not yet resolved, and no promising conclusion can be drawn. Thus, to add to this vast group of studies that have examined bilinguals' performance in task switching, this study has attempted to understand if a bilingual's contextual interaction has any effect on their performance in various switching tasks.

## 4.2 Chapter overview

This chapter starts the investigation into general executive control mechanisms of the participants through the task switching paradigm. In order to do so, the performance of the young adult bilinguals in univalent and bivalent task switching tasks are examined, through the interactional language usage of the participants. The participants are categorised using the premise of the Adaptive Control Hypothesis, and their performance in the switching tasks are compared, based on the language switching habits and the context of their interactional control.

## 4.3 Objective and Hypothesis

The objective of this chapter is to compare the performance of the bilinguals in various switching tasks based on their contextual language usage; to investigate the presence (or lack thereof) of a correlation between language switching frequency and task switching performance. The hypothesis is that the more complex the language switching context, better the performance in task switching.

We are looking at young adult bilinguals with varying frequencies in their language switching to measure their task switching abilities and see if language switching frequency, along with cues, has any role to play in the switch costs of these participants. We systematically conduct two experiments consisting of three tasks. First experiment consisted of a bivalent magnitude/parity numbers task. The second experiment had participants perform 2 tasks, a univalent number/letter task and a bivalent shape/colour task. Thus, total 3 tasks were performed, which are detailed in the sections below.

## 4.4 Experiment 1

This experiment consisted of bilingual young adults performing a magnitude/parity bivalent switching task. The participants were presented with a single digit number on the screen, based on the cue, they had to decide if the number was odd or even (parity task) or lesser than or greater than 5 (magnitude task).

### 4.4.1 Participants

The participants (*n* = 76) were all Bachelor of Technology (B Tech) students. Their ages ranged from 18-25. All participants were bilinguals, the minimum number of languages in a participant's repertoire was 2, with maximum being 7. Participants were taken from different language communities from various parts of the country. All included Hindi and English among the languages they knew along with other languages such as Arabic, Assamese, Bengali, Bhojpuri, Gujarati, Haryanvi, Kannada, Kashmiri, Magahi, Malayalam, Marathi, Marwari, Odia, Punjabi, Rajasthani, Sanskrit, Tamil, Telugu, Tulu, Urdu, etc.

### 4.4.2 Design and Tools

The participants answered 2 questionnaires and perform the task. The first questionnaire was to ascertain the basic information of the participants. Most of the questions in the questionnaire were adapted from LHQ 3 (P. Li et al., 2020) *(see Appendix B).* The purpose of these questions was to determine the linguistic habits of the bilingual participants by gauging their language usage and purpose. Only those questions relevant to the experiment were taken. Questions were asked on language acquisition, ability to pick up languages, extent of their linguistic knowledge and usage, etc.

The second questionnaire was adapted from the Revised Interactional Contexts Questionnaire (Hartanto & Yang, 2020) *(see Appendix D)*. The settings of the contextual language usage are changed to better fit the linguistic situations of the young adult participants. The questionnaire examines the language switching tendencies of the participants in various situations like at home, in school, at social settings, etc. and requires them to rate their switching preference on a scale of 100. The original questionnaire had 4 situations, namely, home, school, work and places other than home, school work. Since the participants of this study were all students, the questionnaire used here asked participants to first score out of 100, the total amount of time they spent at home, school, social interactions, and non-social interactions (could include vendors, cab drivers, etc.). The participants then had to score their interactions in each of the 4 situations (home, school, social interactions and non-social interactions) with respect to the 3 bilingual interactional contexts: Single Language Context (for instance, 'I speak only one language and rarely switch to the other language at home'), Dual Language Context ('I speak 2 or more languages when I converse with different speakers during classes. I often switch languages, but rarely mix languages within a sentence') and Dense Code-Switching Context ('I routinely mix 2 (or more) languages within a sentence to most speakers in a social interaction'). This is then calculated to create a score out of 100 which then will show the participants' tendency towards Single language context, Dual language context or Dense code-switching context.

The task was a simple number switching bivalent task. Numbers from 1 to 9 were on the screen and depending upon the colour of the background on which the number was displayed, the participants had to press the response keys accordingly. If the background colour was green, they had to decide whether the number displayed was odd or even. If the background was red in colour, they had to judge if the number was greater than or lesser than five. The response keys were 'B' and 'N'. The response mapped to the keys were counterbalanced across participants. The task had three conditions (or task blocks): Pure, Alternate and Mixed. Pure condition had parity task (Task A) occurring first in a sequence followed by magnitude task (Task B). Alternate condition had both tasks occurring in AABBAABB sequence. This was followed by Mixed condition where the tasks occurred in a randomized manner.

### 4.4.3 Procedure

This study was underway when Covid-19 pandemic occurred, as a result, this entire experimental procedure had to be conducted online. The experiment was created on E-Prime 3.0, and sent to participants using E-Prime Go 1.0. The participants were sent instructions and links to the questionnaires and the task via mail. They were asked to fill out the questionnaires first, followed by the experiment. The questionnaires were made on SurveyMonkey *[https://www.surveymonkey.com/]*, an online cloud-based survey software.

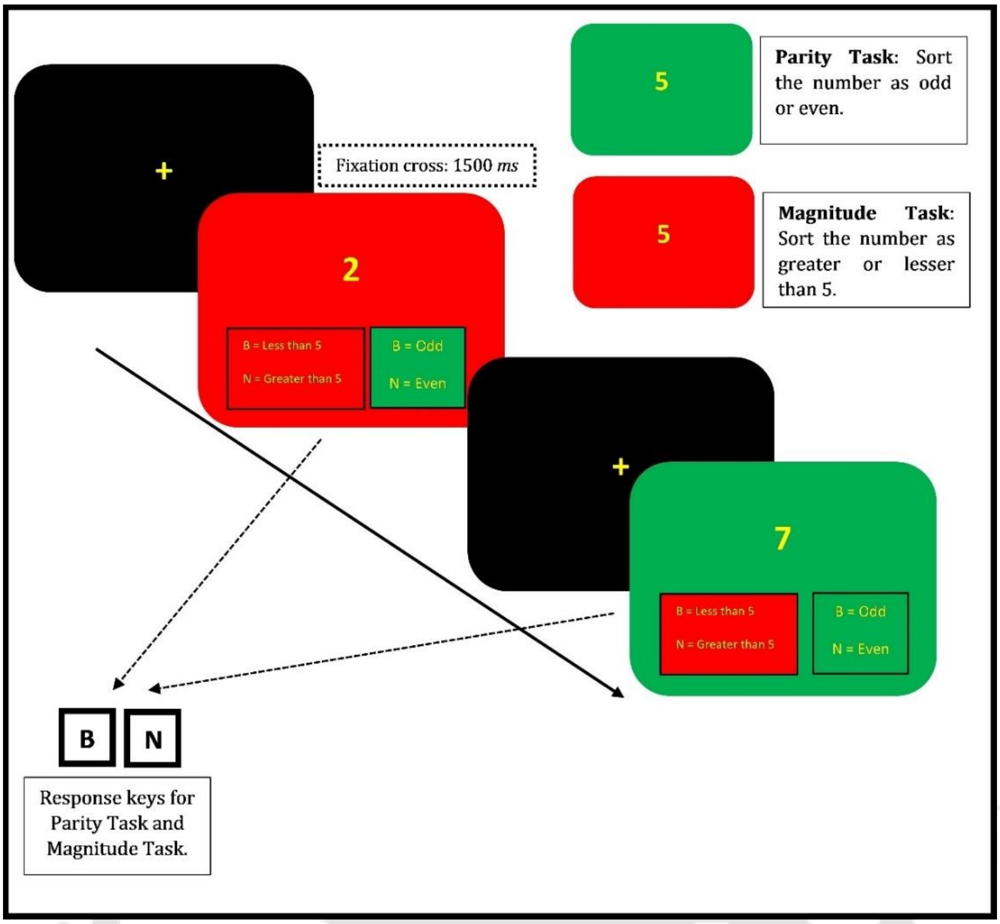


*Figure 4.4.1: Schematic representation of the practice session of the bivalent numbers switching task.*

The participants were first given instructions followed by a practice block consisting of 30 trials, 10 trials for each of the three conditions: Pure, Alternate and Mixed. First, a yellow fixation cross appeared in the centre on a black screen for 1500 *ms* followed by the stimulus. There was no time limit set for stimulus display in the practice session, it stayed on the screen till either B or N was pressed. The cue for which task was to be performed was determined by the background colour of the stimulus display screen. The stimulus screen also showed hints on which task to perform with which background colour *(see Figure 4.5.1)*. Depending upon the response, a feedback slide was displayed for 1500 *ms* informing if the response entered was correct or incorrect, along with the time taken to respond.

They then moved on to the main trial of which they were informed by a slide showing instructions. This was followed by a fixation cross for 1500 *ms* followed by the stimulus. For the main trial the stimulus was displayed for 2500 *ms* after which the feedback slide showed 'No response detected' if the participant did not press any key on time. There was also no hint provided on the stimulus screen. There were total 120 trials, 40 trials for each of the three task conditions- Pure, Alternate and Mixed *(see Figure 4.5.2)*.

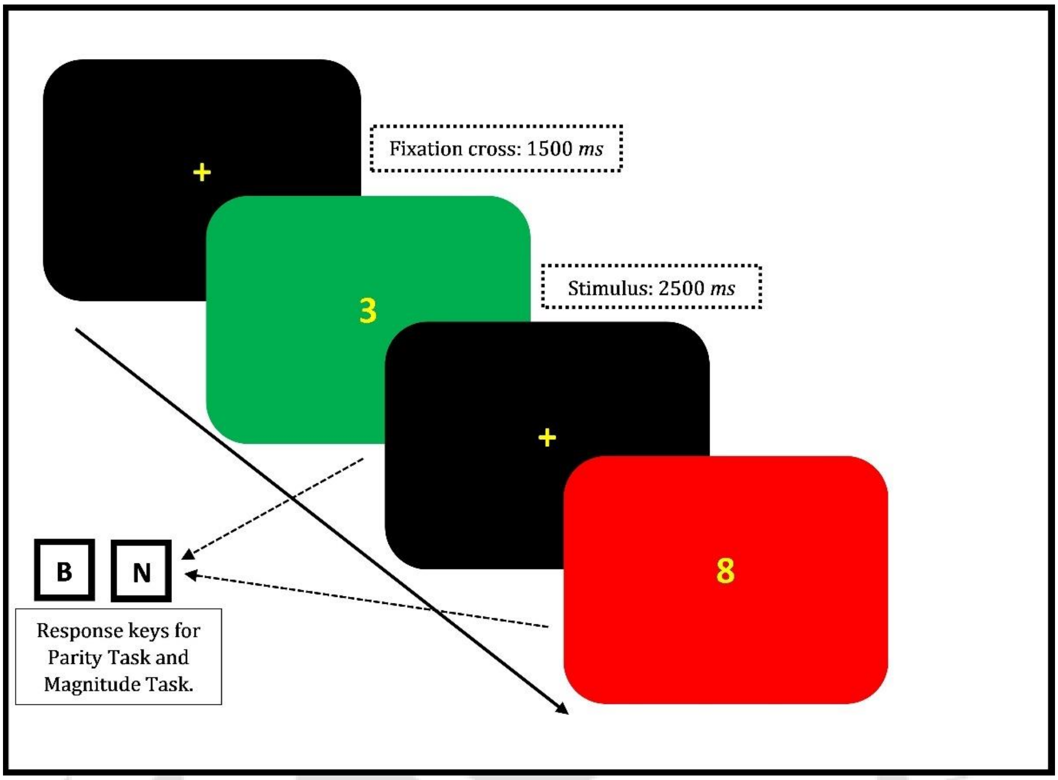


*Figure 4.4.2: Schematic representation of the main session of the bivalent numbers switching task.*

### 4.4.4 Results

*Revised Bilingual Interactional Questionnaire.* The data from the questionnaire was analysed using the method adapted from Hartanto & Yang (2020) *(see Appendix D)*.

The calculations used followed the one proposed by Hartanto & Yang (2020). The percentages in each of the four situations had to add up to 100. Then, for each of the participants, the indices of the 3 language contexts were calculated separately using the following formula:

$$\sum_{i=4}^{4} \frac{p_i \times x_i}{100}$$

Here, $p_i$ denotes the amount of time spent in each of the four situations (home, school, social interaction and non-social interaction), $x_i$ would denote the percentage of a particular language context (single, dual or dense) within each of the 4 given situations. This gave a score for each of the participants in each of the 3 language contexts (Hartanto & Yang, 2020, p. 614). The context in which they scored highest, the participant was assigned to that particular language context. Analysis revealed the 76 participants were divided as: 57 Single Language Context, 7 Dual Language Context, 15 Dense Code-Switching Context.

*Task analysis.* The data was analysed on RStudio (R Core Team, 2024). Analysis was done on the response timings of the participants.

The analysis of the task included a linear mixed model analysis of the overall performance, followed by Type III ANOVA analysis. Since the participants were provided with performance feedback after every trial, Accuracy was also considered as a fixed effect, to see the effect this feedback might have had on their performance. Post HOC tests were performed for further analysis through Estimated Marginal Means and pairwise analysis. Error analysis included performing a generalised linear model analysis on the Accuracy data of the participants, followed by an LMM analysis on the post-error performance of the participants.

### *RT analysis*

*Linear Mixed-Model Analysis*

Using the *lme4* function (Bates et al., 2015) and the *lmerTest* function (Kuznetsova et al., 2017) on RStudio, a linear mixed effects analysis was performed to analyse the relationship between RT and various fixed factors. Models were created with the aim to examine the effect that independent variables LC, Condition and Accuracy had on the response timings of the participants, as well as the interaction effect the independent (or fixed effects) variables had on each other.

At the participant level, the random intercept shows significant variability (variance = 16,784.8, SD = 129.56), indicating that individual differences among participants contribute considerably to the overall variance in the data. The random intercepts for Task (Parity or Magnitude) (variance = 1,394.6, SD = 37.34) and Trial Type (Repeat or Switch) (variance = 4,189.6, SD = 64.73) also showed variability across different tasks and trial types, though to a lesser degree than participant differences. The residual effects show a variance of 91,055.2 (SD = 301.75), which captures unaccounted-for variation. This suggests that there is substantial variation in the model that is not explained by the fixed effects.

Language Context (LC), Condition, and Accuracy were the fixed effects. There were 3 levels in LC (Single, Dual and Dense code-switching), 4 levels in Condition (Pure (Magnitude), Pure (Parity), Alternate, and Mixed), whereas Accuracy had 2 levels (Correct and Error). The random effects included Trial Type (Repeat trials or Switch trials), Task (Magnitude task or Parity task) and Display (stimulus displayed on screen) *(see Table 4.4.1)*.

| *Fixed effects* | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 954.74 | 74.86 | 6.09 | 12.75 | *< .001* |
| ***LC*** | | | | | |
| DLC vs. DCS | 22.14 | 63.43 | 86.99 | 0.35 | .73 |
| DLC vs. SLC | 25.46 | 55.65 | 86.91 | 0.46 | .65 |
| SLC vs. DCS | -3.32 | 40.48 | 87.30 | -0.08 | .93 |
| ***Task condition*** | | | | | |
| Alternate vs. Pure Magnitude | -180.40 | 32.48 | 8561.76 | -5.56 | *< .001* |
| Alternate vs. Pure Parity | -115.29 | 32.12 | 8651.46 | -3.59 | *.0003* |
| Alternate vs. Mixed | -51.30 | 25.93 | 8652.66 | -1.98 | *.05* |
| Pure Magnitude vs. Pure Parity | 65.10 | 37.64 | 8608.42 | 1.73 | *.08* |
| Pure Magnitude vs. Mixed | 129.09 | 32.71 | 8652.88 | 2.95 | *< .001* |
| Pure Parity vs. Mixed | 63.99 | 32.45 | 8650.69 | 1.97 | *.05* |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -192.03 | 38.46 | 8696.21 | -4.99 | *< .001* |
| ***LC x Condition interaction*** | | | | | |
| DLC vs. SLC: Alternate vs. Pure Magnitude | -21.46 | 34.02 | 8652.06 | -0.63 | .53 |
| DLC vs. DCS: Alternate vs. Pure Magnitude | 43.19 | 38.79 | 8652.13 | 1.11 | .27 |
| SLC vs. DCS: Alternate vs. Pure Magnitude | 64.66 | 24.79 | 8652.35 | 2.61 | *.009* |
| DLC vs. SLC: Alternate vs. Pure Parity | 2.98 | 33.62 | 8652.51 | 0.09 | .93 |
| DLC vs. DCS: Alternate vs. Pure Parity | 61.77 | 38.33 | 8652.44 | 1.61 | .11 |
| SLC vs. DCS: Alternate vs. Pure Parity | 58.80 | 24.49 | 8652.22 | 2.40 | *.02* |
| DLC vs. SLC: Alternate vs. Mixed | 47.68 | 27.55 | 8652.40 | 1.73 | *.08* |
| DLC vs. DCS: Alternate vs. Mixed | 91.17 | 31.46 | 8652.38 | 2.90 | *.004* |
| SLC vs. DCS: Alternate vs. Mixed | 43.49 | 20.18 | 8652.35 | 2.16 | *.03* |
| DLC vs. SLC: Pure Magnitude vs. Pure Parity | 24.44 | 39.13 | 8652.16 | 0.63 | .53 |
| DLC vs. DCS: Pure Magnitude vs. Pure Parity | 18.58 | 44.61 | 8652.17 | 0.42 | .68 |
| SLC vs. DCS: Pure Magnitude vs. Pure Parity | -5.86 | 28.48 | 8652.24 | -0.21 | .84 |
| DLC vs. SLC: Pure Magnitude vs. Mixed | 69.15 | 34.13 | 8652.60 | 2.03 | *.04* |
| DLC vs. DCS: Pure Magnitude vs. Mixed | 47.98 | 38.94 | 8652.64 | 1.23 | .22 |
| SLC vs. DCS: Pure Magnitude vs. Mixed | -21.17 | 24.90 | 8652.73 | -0.85 | .40 |
| DLC vs. SLC: Pure Parity vs. Mixed | 44.71 | 33.76 | 8653.47 | 1.32 | .19 |
| DLC vs. DCS: Pure Parity vs. Mixed | 29.40 | 38.47 | 8653.29 | 0.76 | .44 |
| SLC vs. DCS: Pure Parity vs. Mixed | -15.31 | 24.54 | 8652.48 | -0.62 | .53 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | 23.93 | 40.87 | 8697.31 | 0.59 | .55 |
| DLC vs. DCS: Correct vs. Error | -78.82 | 46.82 | 8690.88 | -1.68 | *.09* |
| SLC vs. DCS: Correct vs. Error | -102.75 | 30.06 | 8684.36 | -3.42 | *.0006* |

| *Random effects* | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 16786.0 | 129.56 |
| Display | (Intercept) | 142.4 | 11.93 |
| Task | (Intercept) | 1396.3 | 37.37 |
| Trial Type | (Intercept) | 4189.3 | 64.72 |
| Residual | | 91055.2 | 301.75 |

*Table 4.4.1: LMM results of RT analysis of bivalent numbers task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

For the LC variable, the differences were not significant, for example the contrasts between DLS and DCS showed DLC group was faster by 22.14 *ms* (SE = 63.43, t = 0.35), however, $p$ = .73, thus the difference was not significant. The contrasts between the levels showed that Dual LC group showed faster performance than Single and Dense CSC groups, whereas Dense CSC group had faster performance than Single LC group.

Task conditions showed significant differences between the levels, for instance, Alternate task condition differed from Pure (Magnitude) where performance in Pure (Magnitude) was significantly faster by 180.40 *ms* (SE = 32.48, t = -5.56), with $p < .001$. Comparison between levels showed that other levels had faster performance compared to Alternate task condition, Pure (Magnitude) showed significantly faster performance than Pure (Parity), as well as Mixed task conditions, and Pure (Parity) showed faster performance than Mixed task condition.

When it came to interaction between LC and Task condition, statistical significance was found only on comparison between certain levels, for instance, when comparing Single LC group with Dense CSC group, in their performance in Alternate vs Pure (Magnitude) showed an estimated difference of 64.66 *ms* (SE = 24.79, t = 2.61), with $p = .009$. The non-significance of interactions in other cases suggest that perhaps the effect of task condition is relatively stable across the different LC levels.

*ANOVA*

A Type III ANOVA *(table 4.4.2)* was conducted to evaluate the effects of language context (LC), task condition, and accuracy, as well as their interactions, on the dependent variable, RT. The analysis included main effects for LC, condition, and accuracy, along with interactions between LC and condition and LC and accuracy.

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 61393 | 30696 | 2 | 89.7 | 0.34 | .71 |
| ***Condition*** | 16003322 | 5334441 | 3 | 8245.2 | 58.58 | < *.001* |
| ***Accuracy*** | 15183092 | 15183092 | 1 | 8692.4 | 166.75 | < *.001* |
| ***LC: Condition*** | 1435974 | 239329 | 6 | 8652.5 | 2.63 | *.02* |
| ***LC: Accuracy*** | 1064025 | 532012 | 2 | 8690.7 | 5.84 | *.003* |

*Table 4.4.2: Type III Analysis of Variance Table with Satterthwaite's method of bivalent numbers task.*

The main effect of LC was not statistically significant, F(2, 89.7) = 0.34, with $p = .71$, suggesting that there were no significant differences between the levels of LC on the reaction times of the participant. The main effect of task condition was significant, where F(3, 8245.2) = 58.58, and $p < .001$, indicating that reaction times differed significantly across the various task conditions. The main effect of accuracy was also significant, F(1, 8692.4) = 166.75, with $p < .001$, suggesting that the accuracy of responses significantly influenced the dependent variable.

There was a significant interaction between LC and task condition, F(6, 8652.5) = 2.63, with *p* = .02, indicating that the effect of LC on RT varied depending on the condition. The interaction between LC and accuracy was also significant, F(2, 8690.7) = 5.84, *p* = .003, suggesting that the effect of LC on RT differed depending on accuracy levels.

The results indicate that task condition and accuracy have significant main effects on the reaction time, meaning that both condition and accuracy significantly affect performance of the participants. However, the non-significance of LC suggests that, on its own, LC does not have a significant effect on performance.

### *Post-HOC Analysis*

A post HOC analysis was performed for a better understanding of the analysis done above. For this, Estimated Marginal Means was used.

*EM Means- Language context*

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 817 | 56.8 | 2.05 | 578 | 1055 |
| ***Dual*** | 772 | 75.2 | 6.18 | 589 | 955 |
| ***Dense*** | 804 | 64.6 | 3.42 | 612 | 996 |

*Table 4.4.3: Group-wise EM Means based on Language Context in overall performance in bivalent numbers task.*

EM means was performed for the different levels of language context (LC) groups *(see Table 4.4.3)*. For the Dual LC condition, the mean response time was772 *ms*, (SE = 75.2, df = 6.18, 95% CI [589, 955]. Dense CSC group had an estimated marginal mean RT of 804 *ms* (SE = 64.6, df = 3.42, 95% CI [612, 996]. Finally, the estimated marginal mean RT for Single LC group was 817 *ms* (SE = 56.8, df = 56.8, 95% CI [578, 1055]. These results indicate that there is some variability in response times across different LSC types, with Dual LC group showing the lowest mean, followed by Dense CSC group and then finally Single LC group *(see figure 4.5.3 for graphical representation)*.

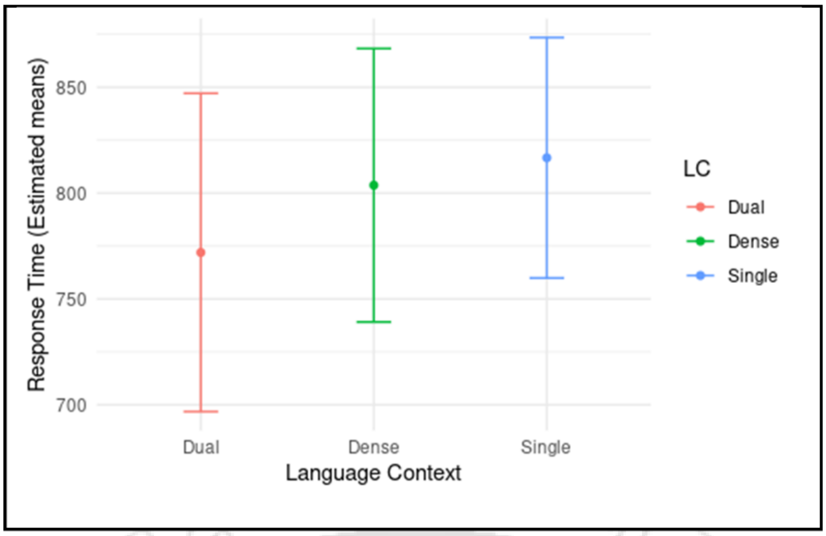


*Figure 4.4.3: Group-wise EM Means based on Language Context in overall performance in bivalent numbers task. Dual LC group shows fastest performance, followed by Dense CSC group, finally the Single LC group. Bars represent 95% confidence intervals.*

*Pairwise analysis- Language context*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -31.8 | 63.9 | 89.8 | -0.50 | 0.87 |
| ***Dual - Single*** | -44.7 | 56.1 | 89.5 | -0.80 | 0.71 |
| ***Dense - Single*** | -13.0 | 40.8 | 90.1 | -0.32 | 0.95 |

*Table 4.4.4: Pair-wise analysis based on Language context in overall performance in bivalent numbers task.*

A pairwise comparison was conducted to examine the differences in response times between the Dual, Dense, and Single LC groups *(see Table 4.4.4)*. The comparison between the Dual LC and Dense CSC was not statistically significant, with an estimated difference of 31.8 *ms,* (SE = 63.9, df = 89.8, t = −0.50), with $p$ = .87, where the performance in Dual LC group was faster than Dense CSC group but not significantly so. Similarly, the difference between the Dual and Single conditions was not significant, with a difference of 44.7 *ms* (SE = 56.1, df = 89.5, t = −0.80), $p$ = .71, where a faster performance was seen in Dual LC group. Finally, the comparison between the Dense and Single conditions was also not significant, with an estimated difference 13 *ms* (SE = 40.8, df = 90.1, t = -0.32), with $p$ = .95, where Dense CSC group showed a faster performance.

Thus, none of the pairwise comparisons between the Dual, Dense, and Single LC conditions showed statistically significant differences in response times, indicating that the LC conditions did not significantly differ from one another in terms of performance.

*EM Means- Task condition*

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Pure (Magnitude)*** | 692 | 59.1 | 2.40 | 450 | 910 |
| ***Pure (Parity)*** | 772 | 59.1 | 2.40 | 554 | 990 |
| ***Alternate*** | 865 | 58.3 | 2.27 | 641 | 1090 |
| ***Mixed*** | 860 | 58.2 | 2.26 | 636 | 1085 |

*Table 4.4.5: Group-wise EM Means based on task condition in overall performance in bivalent numbers task.*

The estimated marginal means (EM means) for reaction times across different task conditions were performed *(Table 4.4.5)*. Pure (Magnitude) condition had an EM mean of 692 *ms* (SE = 59.1, df = 2.40, 95% CI [450, 910]). Pure (Parity) had an estimated mean of 772 *ms* (SE = 59.1, df = 2.40, 95% CI [554, 990]). Mixed task condition had an estimated mean of 860 *ms* (SE = 58.2, df = 636, 95% CI [636, 1085]). Finally, Alternate task condition showed the highest EM mean at 865 *ms* (SE = 58.3, df = 2.27, 95% CI [641, 1090] *(see Figure 4.5.4 for graphical representation)*.

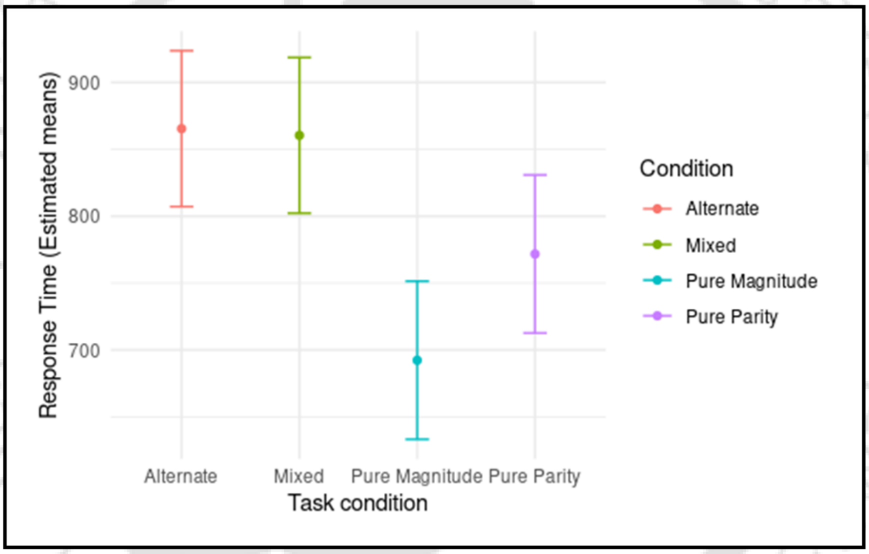


*Figure 4.4.4: Group-wise EM Means based on task-wise performance in bivalent numbers task. Performance in Pure (Magnitude) condition is seen to be fastest, and performance in Alternate task condition slowest. Bars represent 95% confidence intervals.*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Pure (Magnitude) - (Pure Parity)*** | -79.44 | 17.5 | 7588 | -4.54 | < *.0001* |
| ***Alternate - Pure (Magnitude)*** | 173.15 | 14.6 | 8519 | 11.84 | < *.0001* |
| ***Alternate - Pure (Parity)*** | 93.71 | 14.6 | 8480 | 6.44 | < *.001* |
| ***Alternate - Mixed*** | 5.02 | 11.0 | 8654 | 0.46 | .97 |
| ***Mixed - Pure (Magnitude)*** | 168.14 | 15.0 | 8532 | 11.23 | < *.0001* |
| ***Mixed - Pure (Parity)*** | 88.69 | 15.0 | 8423 | 5.90 | < *.0001* |

*Table 4.4.6: Pair-wise analysis based on task condition in overall performance in univalent task.*

*Pairwise analysis- Task condition*

A pairwise comparison analysis was conducted to examine differences in reaction times between various task conditions *(Table 4.4.6)*. The reaction times were significantly shorter in the Pure (Magnitude) condition compared to the Pure (Parity) condition, with an estimated difference of 79.44 *ms* (SE = 17.5, df = 7588, t = -4.54), with $p < .0001$. On the other hand, RTs were significantly longer in the Alternate condition compared to the Pure (Magnitude) condition with an estimated difference of 173.15 *ms* (SE = 14.6, df = 8519, t = 11.84), with $p < .0001$, as well as compared to Pure (Parity) condition where there was an estimated difference of 93.71 *ms* (SE = 14.6, df = 8480, t = 6.44), with $p < .001$, thus highlighting the increased difficulty or complexity associated with the Alternate condition.

### Accuracy analysis

*Error rate.* Error-rate analysis revealed that Dense CSC group had the least errors (8.48%), closely followed by Dual LC group (8.95%), and then came Single LC group (9.22%).

*GLMM.* To further investigate the role of accuracy in participants' performances, a generalized linear mixed model was conducted to examine the effects of language context (LC), task condition (Condition), and scaled reaction time (RT) on accuracy, with random intercepts for participants and trial type. RT was scaled to match the values of the other variables for better convergence of the model.

The random effects revealed significant variability across individual participants with a variance of 0.61 (SD = 0.78) and in Trial Type, with a variance of 0.08 (SD = 0.29), indicating that accuracy varied between individual participants, as well as between trial types.

Fixed effects analysis was done on LC, task condition, and accuracy. Analysis of LC showed that none of the comparisons among the LC levels showed statistical significance. Dual LC group had greater accuracy than Single LC group and Dense CSC group. Single LC group had a lower accuracy rate than Dense CSC group. Analysis of the task condition levels showed that comparison between Mixed task condition and Pure (Parity) showed a significant difference, with an estimate of 0.91 (SE = 0.44, z = 2.05), with $p = .04$, where Mixed task condition had lower accuracy rate than Pure (Parity). Comparing other levels showed that the differences among them was not statistically significant. It was found that performance in Alternate task condition had a lower accuracy rate than Pure (Magnitude) and Pure (Parity). Alternate condition had a higher accuracy rate than Mixed task condition, and Pure (Parity) had higher accuracy than Pure (Magnitude).

The effect of RT (scaled) was highly significant, with an estimate of -0.62 (SE = 0.04, z = -14.05), with $p < .001$, indicating that as RT decreased, the likelihood of the response given being correct also decreased.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -2.74 | 0.43 | -6.36 | < *.001* |
| ***LC*** | | | | |
| DLC vs. DCS | 0.11 | 0.46 | 0.23 | .82 |
| DLC vs. SLC | 0.11 | 0.40 | 0.27 | .79 |
| SLC vs. DCS | -0.002 | 0.29 | -0.008 | .99 |
| ***Task condition*** | | | | |
| Alternate vs. Pure (Magnitude) | -0.38 | 0.44 | -0.87 | .38 |
| Alternate vs. Pure (Parity) | -0.45 | 0.46 | -0.98 | .33 |
| Alternate vs. Mixed | 0.46 | 0.30 | 1.52 | .13 |
| Pure (Magnitude) vs. Pure (Parity) | -0.07 | 0.54 | -0.13 | .90 |
| Pure (Magnitude) vs. Mixed | 0.84 | 0.42 | 1.99 | *.05* |
| Pure (Parity) vs. Mixed | 0.91 | 0.44 | 2.05 | *.04* |
| ***Response time*** | | | | |
| RT (scaled) | -0.62 | 0.04 | -14.05 | < *.001* |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Alternate vs. Pure (Magnitude) | -0.43 | 0.47 | -0.93 | .35 |
| DLC vs. DCS: Alternate vs. Pure (Magnitude) | -0.79 | 0.59 | -1.36 | .18 |
| SLC vs. DCS: Alternate vs. Pure (Magnitude) | -0.36 | 0.42 | -0.84 | .40 |
| DLC vs. SLC: Alternate vs. Pure (Parity) | 0.65 | 0.48 | 1.37 | .17 |
| DLC vs. DCS: Alternate vs. Pure (Parity) | 0.83 | 0.52 | 1.59 | .11 |
| SLC vs. DCS: Alternate vs. Pure (Parity) | 0.18 | 0.29 | 0.63 | .53 |
| DLC vs. SLC: Alternate vs. Mixed | -0.22 | 0.32 | -0.68 | .50 |
| DLC vs. DCS: Alternate vs. Mixed | -0.15 | 0.37 | -0.40 | .69 |
| SLC vs. DCS: Alternate vs. Mixed | 0.07 | 0.24 | 0.29 | .77 |
| DLC vs. SLS: Pure (Magnitude) vs. Pure (Parity) | 1.09 | 0.57 | 1.91 | *.06* |
| DLC vs. DCS: Pure (Magnitude) vs. Pure (Parity) | 1.63 | 0.68 | 2.40 | *.02* |
| SLC vs. DCS: Pure (Magnitude) vs. Pure (Parity) | 0.54 | 0.45 | 1.20 | .23 |
| DLC vs. SLC: Pure (Magnitude) vs. Mixed | 0.22 | 0.45 | 0.49 | .62 |
| DLC vs. DCS: Pure (Magnitude) vs. Mixed | 0.65 | 0.57 | 1.14 | .25 |
| SLC vs. DCS: Pure (Magnitude) vs. Mixed | 0.42 | 0.42 | 1.02 | .31 |
| DLC vs. SLC: Pure (Parity) vs. Mixed | -0.87 | 0.46 | -1.91 | *.06* |
| DLC vs. DCS: Pure (Parity) vs. Mixed | -0.98 | 0.50 | -1.96 | *.05* |
| SLC vs. DCS: Pure (Parity) vs. Mixed | -0.11 | 0.28 | -0.40 | .69 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Group** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.61 | 0.78 |
| Trial Type | (Intercept) | 0.08 | 0.29 |

*Table 4.4.7: GLMM results of error analysis of bivalent numbers task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

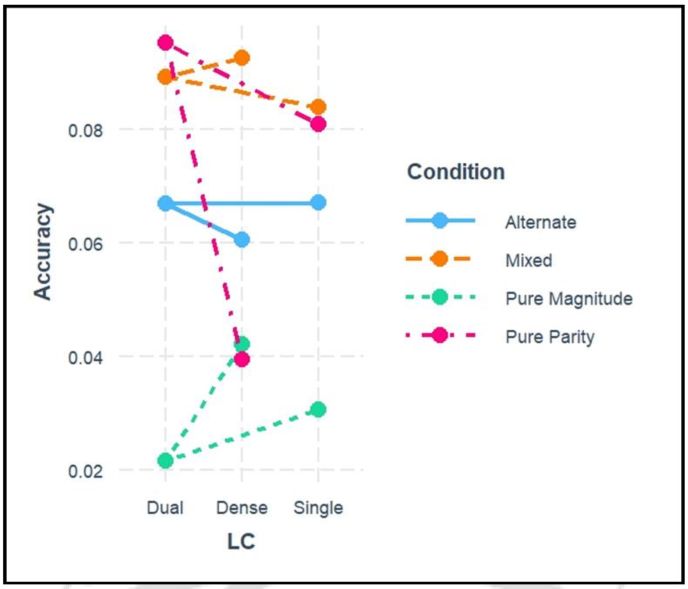


*Figure 4.4.5: Graph showing error analysis of bivalent numbers task. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

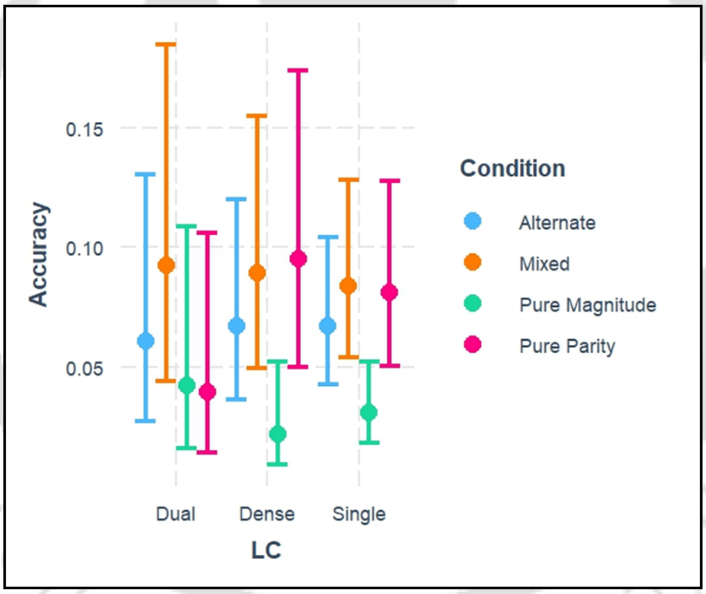


*Figure 4.4.6: Error analysis of each LC group in bivalent numbers task performance. Each coloured bar represents a different task condition.*

Most of the LC and task condition interactions were not statistically significant. Some comparisons were significant, such as between Dual LC group and Dense CSC group, comparing their performance in Pure (Magnitude) and Pure (Parity) conditions, which yielded an estimated difference of 1.63 (SE = 0.68, z = 2.40), with p = .02. This suggests that neither the differences between LC groups, task conditions or the interactions between LC and task conditions have a very strong influence on the accuracy of the performance.

### ***Post-error analysis***

A linear mixed-effects model was conducted to examine the effects of post-error response, local context (LC), condition, and their interactions on reaction time (RT). The model included random intercepts and slopes for post-error effects across participants and random intercepts for trial types.

The random effects revealed substantial variation in reaction times across participants (Variance = 17,116, SD = 130.83). The correlation between the intercept and slop of Post-error performance was positive, but weak (corr = 0.15), indicating that participants with faster reaction times had slightly stronger post-error effects, that is, slower reaction times after errors. Additionally, there was variability across trial types (Variance = 3,795, SD = 61.61). The residual variance was 93468 (SD = 305.73), suggesting a considerable amount of unexplained variability.

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 920.14 | 67.03 | 5.37 | 13.73 | < *.0001* |
| Post error | 9.94 | 52.16 | 83.52 | 0.19 | .85 |
| ***LC*** | | | | | |
| DLC vs. DCS | 53.21 | 61.42 | 70.98 | 0.87 | .39 |
| DLC vs. SLC | 37.63 | 53.91 | 70.98 | 0.70 | .49 |
| SLC vs. DCS | 15.58 | 39.17 | 71.03 | 0.40 | .69 |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Magnitude) | -210.63 | 10.97 | 8514.28 | -19.20 | < *.001* |
| Alternate vs. Pure (Parity) | -88.34 | 11.06 | 8519.84 | -7.99 | < *.001* |
| Alternate vs. Mixed | -2.70 | 8.53 | 8608.87 | -0.32 | .75 |
| Pure (Magnitude) vs. Pure (Parity) | 122.29 | 11.76 | 8603.68 | 10.40 | < *.001* |
| Pure (Magnitude) vs. Mixed | 207.93 | 11.51 | 8397.19 | 18.07 | < *.001* |
| Pure (Parity) vs. Mixed | 85.63 | 11.60 | 8404.62 | 7.39 | < *.001* |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | 29.72 | 52.31 | 65.77 | 0.57 | .57 |
| Post error: DLC vs. DCS | 113.05 | 59.67 | 67.60 | 1.90 | *.06* |
| Post error: SLC vs. DCS | 83.33 | 38.21 | 69.62 | 2.18 | *.03* |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Alternate vs. Pure (Magnitude) | 104.56 | 44.69 | 7959.15 | 2.34 | *.02* |
| Post error: Alternate vs. Pure (Parity) | 92.776 | 33.88 | 6720.12 | 2.74 | *.006* |
| Post error: Alternate vs. Mixed | -39.59 | 27.75 | 6156.54 | -1.43 | .15 |
| Post error: Pure (Magnitude) vs. Pure (Parity) | -11.78 | 48.01 | 7711.77 | -0.25 | .81 |
| Post error: Pure (Magnitude) vs. Mixed | -144.15 | 43.88 | 7788.36 | -3.29 | *.001* |
| Post error: Pure (Parity) vs. Mixed | -132.37 | 32.68 | 6262.26 | -4.05 | < *.001* |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Corr** |
| Subject | (Intercept) | 17116 | 130.83 | |
| | Post error | 5046 | 71.04 | 0.15 |
| Trial Type | (Intercept) | 3795 | 61.61 | |
| Residual | | 93468 | 305.73 | |

*Table 4.4.8: LMM results of post-error performance in bivalent numbers task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

The post-error effect was not statistically significant, with an estimate of 9.94 (SE = 52.16, t = 0.19), however, $p$ = .85, suggesting that there was no significant difference in RT following an error.

The interaction between post-error performance and LC revealed that Dual LC group had slower post-error response than Single LC group and Dense CSC group. The post-error performance comparison between Dual LC group and Dense CSC group had an estimated difference of 113.05 *ms* (SE = 59.67, t = 1.90), with $p$ = .06, where performance in Dual LC group was slower than Single LC group. Dual LC group also showed slower post-error performance than Single LC group. Single LC group had a slower performance than Dense CSC group, but this difference was not statistically significant.

The interaction between post-error performance and task condition shows significance in comparison between few levels. For instance, comparing post-error performance of Pure (Parity) task condition with Mixed task condition showed an estimated difference of 132.37 *ms* (SE = 32.68, t = -4.05), with $p$ < .001, where performance in Mixed task condition was slower. Similarly, when comparing Mixed task condition with Pure (Magnitude), there was an estimated difference of 144.15 *ms* (SE = 43.88, t = -3.29), with p = .001, where performance in Mixed task condition was slower. Mixed task condition also showed slower performance than Alternate task condition, but this difference was not statistically significant. Alternate task condition had slower post-error performance than Pure (Magnitude) and Pure (Parity). Pure (Parity) showed slower performance than Pure (Magnitude) in post-error performance.

In summary, the analysis showed that the fixed effects groups of both, LC and task conditions showed a significant influence in the post-error performance, but this was not evident for comparison between all levels.

### 4.4.5 Discussion

The aim of this experiment was to observe the relationship between contextual language usage and task switching, and investigate the presence of any spillover effects into one's general executive control functioning.

A basic analysis of the task included ANOVA and post HOC estimated marginal means analysis. Overall, it was observed that Dual LC group showed the fastest performance, followed by Single LC and then Dense CSC group. The Dual LC group outperformed the other groups in all the three task conditions. They showed fastest performance in Pure condition, followed by Mixed condition and then Alternate condition. Single LC group performed better than Dense CSC group in Pure condition and marginally so in Mixed condition. Participants of Dense CSC group showed better performance than those of Single LC in Alternate condition. The preliminary analysis aligned with the premise of the Adaptive Control Hypothesis, with the Dual language context group showed better performance than the Single language and Dense code-switching context group, an outcome visible despite the imbalance in the number of participants in each group. Interestingly, Dense CSC group showed better performance than the Single LC group in Alternate task condition, and showed very small difference in performance in Mixed group. This could be because the frequently switching tasks in both the task conditions were similar to the language switching mechanism habitual of the Dense CSC group.

As observed from the analysis above, this experiment also faced a few limitations, leading to a lack of clear conclusion. First, since this experiment was conducted online entirely, data of 17 people had to be discarded due to technical errors during data collection. Second issue was the division of the participants. Based on their performance in one questionnaire, the participants were divided in 3 groups. However, due to uneven distribution of the participants among the three groups, results came out skewed because while one group has 57 participants, the other 2 groups have 15 and 7 respectively.

One reason for majority of the participants being categorized in the single category could be due to the fact that the data was collected during peak lockdown period when everyone was at home and had minimal interaction in languages other than their own, outside of their home therefore making them mostly single language users.

Keeping these limitations from this experiment in mind, the next experiment was conducted in a more careful manner. Firstly, all data was collected offline, on a single laptop so that data was not lost in transmission. Secondly, a wider age range of participants were chosen to give a more rounded perspective. Thirdly, when the experiment was conducted, the lockdown had lifted slightly, allowing for the participants to have more interaction than just home, therefore opening up their spectrum of interaction to resume to normalcy.

## 4.5 Experiment 2

### 4.5.1 Participants

There were total of 61 participants who took part in the experiment. The participants were all between the ages of 18-30. They were all bi/multilinguals with at least 2 languages in their repertoire, Hindi and English. Other languages that the participants spoke Assamese, Bangla, Boro, Bhojpuri, Kannada, Kuki, Malayalam, Marathi, Meitei, Mizo, Vaiphei, etc.

### 4.5.2 Design and Tools

The first questionnaire was a participant history questionnaire which enquires about their basic history like age, handedness, educational level, language history, etc *(see Appendix B)*. It asked questions about the participants' language history and usage.

The second questionnaire is same as the one used above in the previous experiment, adapted from the Revised Interactional Contexts Questionnaire (Hartanto & Yang, 2020). Based on the responses, the participants were divided into the three groups for the purpose of analysis *(see Appendix D)*.

*Univalent Switching Task*. Both the tasks were designed on E-Prime 3. In a univalent task, the two (or more) tasks to be performed have completely different set of stimuli with no overlap whatsoever. The cue presented as well as the response keys assigned to each task are separate. In this particular experiment, the univalent task was a Number-Letter task *(see Figure 4.5.1 for schematic diagram)*. So, the two stimuli were either letters for the Letter task and numbers for the Number task. Since the presence of the stimuli were self-explanatory, there was no requirement for a cue to state the task. The response keys assigned to each task were also completely different.

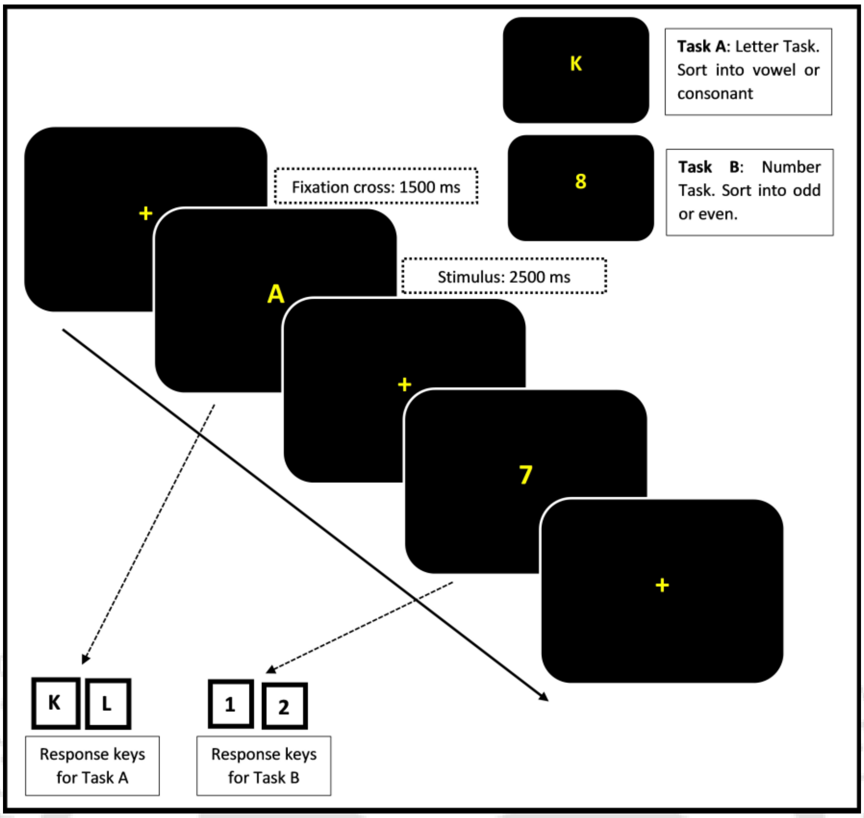


*Figure 4.5.1: Schematic diagram of Univalent task performed.*

Depending upon the task to be performed, the stimuli consisted of either number (1 to 9), or capital letters (consonants: H, M, R, T, V, Y; vowels: A, E, U). Vowels 'I' and 'O' were not included to avoid confusion between letters 'I' and 'O' and numbers '1' and '0'. Consonants were specifically chosen to look as different from numbers as possible to avoid confusion. The stimuli were yellow in colour and presented on a black background. The display on the practice session displayed the keys and their respective responses. For the main session, the screen displayed just the stimuli. The tasks consisted of categorizing the numbers presented as 'odd' or 'even', and the alphabets as 'consonants' and 'vowels', with emphasis on speed and accuracy. Keys 'K', 'L', '1' and '2' were used as response keys for the task. For the Letter task, keys 'K', and 'L' were used and for Number task keys '1', and '2' were used. The response attached to the keys were counterbalanced across subjects, while keeping the choice fixed across number and letter category. This means that response key 1 & 2 were counterbalanced across subjects and these are two keys always used for number tasks, and not for letter tasks. Similar counterbalancing was done for the letter task response keys too.

*Bivalent Switching Task.* Unlike the univalent task, the bivalent task consists of a single set of stimuli upon which 2 different kinds of tasks need to be performed. The task to be performed is determined by the cue which corresponds to the task. The response keys to both the tasks require the same set of response keys. Therefore, in a bivalent task, the stimulus and the response keys remain the same, while the different cues determine which task is required to be performed.

For this particular experiment, the stimuli were common for both the tasks. They were: blue circle, red circle, blue square and red square *(see Figure 4.5.2 for schematic diagram)*. The two shapes, square and circle, were chosen because of their dissimilarity and lack of ambiguity in judgement. The two colours, red and blue, were also similarly chosen. The background colour was black. The fixation cross (+) as well as the text displaying the task cue were yellow in colour. Just like in the previous experiment, this experiment also had a practice session and a main session. The display on the practice session displayed the keys and their respective responses. For the main session, the screen simply displayed the stimuli.

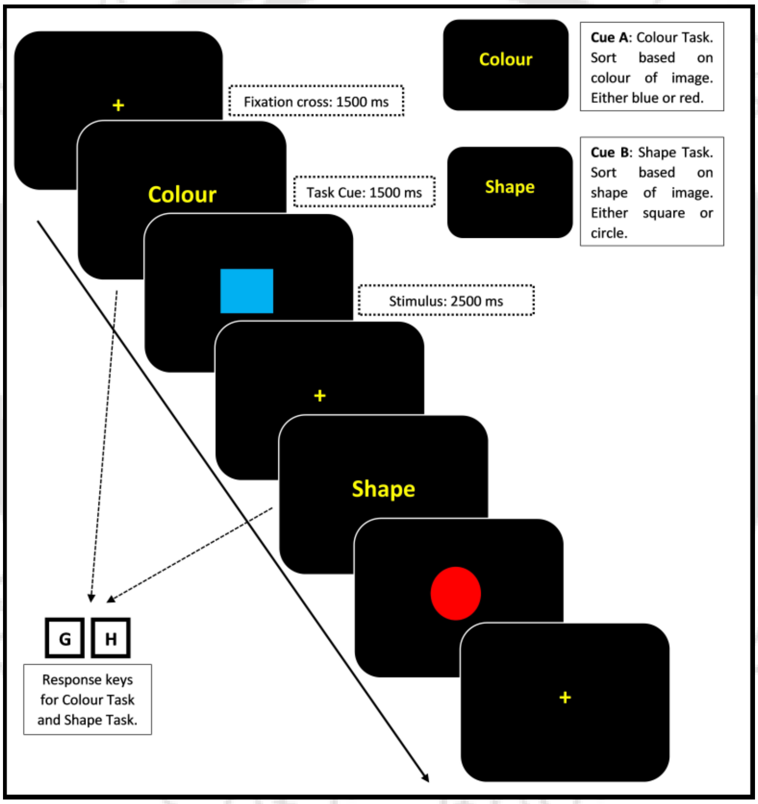


*Figure 4.5.2: Schematic diagram of Bivalent task performed.*

The two tasks in this experiment were Colour and Shape tasks. Depending upon the cue word that preceded the stimulus, the task was to categorize the figure based on its colour or shape. If the cue said 'Colour' the task was to categorize the figure as red or blue. If the cue was 'Shape' the task was to decide if the figure shown was a square or a circle. The response keys for both the tasks were keys 'G' and 'H'. The response attached to the keys were counterbalanced across subjects.

### 4.5.3 Procedure

The participants were asked to perform the two switching tasks: Univalent and Bivalent task switching tasks, as well as fill two sets of questionnaires that were aimed at getting the background information about the participants, with regard to language switching behaviour and general language history. The participants performed the tasks on E-Prime 3 on a 13-inch laptop. They performed the two tasks on two separate days. Half the participants performed the Univalent task first followed by the Bivalent task, whereas the other half performed Bivalent task and then the Univalent task. Both the tasks had a practice session followed by the main session. The participants were first presented with the instructions on how to do the experiment. This was followed by a brief practice session to familiarize them with the task. Finally, they performed the main session.

For both, the practice and the main sessions, there were 3 blocks. In the Pure block, the participant had to first perform the one task for a certain number of trials, followed by the other task. This was then followed by Alternate block, which followed the sequence of AABB, meaning, two of one task followed by two of the other. Finally, the third block was the Mixed block, where both the tasks were presented in a randomized manner.

The practice session had a total of 30 trials, 10 for each block. After the set of instructions were displayed, the participants were first given some practice trials. First, a fixation cross (+) appeared on the screen for 1500 *ms* which was followed by the cue word which was on the screen for 1500 *ms*. This was then followed by the stimulus. The practice session had no time limit for the stimulus, which stayed on the screen until the participant gave a response. In the practice session, the screen showing the stimulus also displayed the cues for response keys to corresponding tasks. A feedback screen followed, displaying whether the response given was correct or incorrect.

The main session had 120 trials in total. First, there were 40 trials in Pure block: 20 trials each task, followed by 40 trials of Alternate block, and finally, 40 trials in Mixed block where each of the tasks occurred equally but in a randomized manner. Similar to the practice session, a fixation cross appeared at the centre of the screen for 1500 *ms* followed by the cue indicating which task to perform. Then, the stimulus appeared on the screen for 2500 *ms*. If no response was detected within the time it was taken as an incorrect response. For the main session, there were no hints for the response keys and their corresponding responses. The screen only showed the stimulus image. This was followed by the feedback screen which informed the participants whether the responses they gave was correct, incorrect or if no responses were detected.

### 4.5.4 Results

*Revised Bilingual Interactional Questionnaire.* The data from the questionnaire was analysed using the method adapted from (Hartanto & Yang, 2020). The analysis of the questionnaire data was done as previously mentioned in section 4.3.4. Analysis revealed the 61 participants were divided as: 21 Single Language Context, 19 Dual Language Context, 21 Dense Code-Switching Context.

#### 4.5.4.1 Univalent Task

The data was analysed on RStudio (R Core Team, 2024). Analysis was done on the reaction time (RT) of the participants. For both the switching tasks, the analysis was done on overall performance, local switch cost and global switch cost. For each of these three parameters, analysis was done on both, speed as well as accuracy of the performance. For speed performance, analysis included linear mixed model, and Type III ANOVA. This was followed by a post-HOC test of EM Means and pairwise analysis. For accuracy, analysis included a generalised linear mixed analysis as well as post-error analysis.

***RT Analysis***

*Linear Mixed-Model Analysis*

A linear mixed effects analysis was performed to analyse the relationship between RT and various fixed factors. Models were created with the aim to examine the effect that independent variables LC, Condition and Accuracy had on the response timings of the participants, as well as the interaction effect the independent variables (or fixed effects) had on each other.

Language Context (LC), Condition, and Accuracy were the fixed effects. There were 3 levels in LC (Single, Dual and Dense code-switching) and 4 levels in task condition (Pure (Letter), Pure (Number), Alternate, and Mixed), whereas Accuracy had 2 levels (Correct and Error). The random effects were Trial Type (Repeat or Switch), Task, Display, and Participants.

The random effects for the mixed-effects model were examined across several grouping variables, including Subject, Display, Task, and Trial Type. The intercept variance for Subject was 13,745.0 (SD = 117.24), indicating substantial variability between subjects. The variance for Display was 1,434.2 (SD = 37.87), showing moderate variability across different displays. Task had a variance of 626.6 (SD = 25.03), suggesting smaller but non-negligible variability between tasks. Trial Type showed a variance of 3,548.7 (SD = 59.57), indicating considerable variability between different trial types. The residual variance was 45,903.7 (SD = 214.25), reflecting the remaining unexplained variability at the observation level. Together, these results suggest that individual differences between subjects, displays, tasks, and trial types contribute variably to the overall model, with the highest variance attributed to individual participants.

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 890.42 | 54.37 | 2.60 | 16.38 | *.001* |
| ***LC*** | | | | | |
| DLC vs. DCS | 76.71 | 38.79 | 65.19 | 1.98 | *.05* |
| DLC vs. SLC | 64.03 | 38.79 | 65.17 | 1.65 | .10 |
| SLC vs. DCS | 12.68 | 37.84 | 65.42 | 0.34 | .74 |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Letter) | -44.73 | 14.69 | 6728.36 | -3.04 | *.002* |
| Alternate vs. Pure (Number) | -59.38 | 14.70 | 6747.79 | -4.04 | *< .001* |
| Alternate vs. Mixed | -36.91 | 11.21 | 6782.84 | -3.29 | *.001* |
| Pure (Letter) vs. Pure (Number) | -14.66 | 17.30 | 6316.55 | -0.85 | .40 |
| Pure (Letter) vs. Mixed | 7.82 | 14.69 | 6726.48 | 0.53 | .59 |
| Pure (Number) vs. Mixed | 22.48 | 14.71 | 6747.24 | 1.53 | .13 |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -39.19 | 21.05 | 6792.28 | -1.86 | *.06* |
| ***LC x Condition interaction*** | | | | | |
| DLC vs. SLC: Alternate vs. Pure (Letter) | 41.76 | 19.24 | 6775.63 | 2.17 | *.03* |
| DLC vs. DCS: Alternate vs. Pure (Letter) | -9.02 | 19.18 | 6775.66 | -0.47 | .64 |
| SLC vs. DCS: Alternate vs. Pure (Letter) | -50.78 | 18.85 | 6776.05 | -2.70 | .007 |
| DLC vs. SLC: Alternate vs. Pure (Number) | -51.72 | 19.27 | 6775.46 | -2.68 | *.007* |
| DLC vs. DCS: Alternate vs. Pure (Number) | -46.26 | 19.36 | 6775.34 | -2.39 | *.02* |
| SLC vs. DCS: Alternate vs. Pure (Number) | 5.46 | 18.94 | 6775.60 | 0.29 | *.77* |
| DLC vs. SLC: Alternate vs. Mixed | -23.52 | 15.56 | 6775.55 | -1.51 | *.13* |
| DLC vs. DCS: Alternate vs. Mixed | -5.52 | 15.57 | 6775.46 | -0.35 | .72 |
| SLC vs. DCS: Alternate vs. Mixed | 18.00 | 15.33 | 6775.71 | 1.17 | .24 |
| DLC vs. DCS: Pure (Letter) vs. Pure (Number) | -93.48 | 22.26 | 6775.33 | -4.20 | *< .001* |
| DLC vs. SLC: Pure (Letter) vs. Pure (Number) | -37.23 | 22.30 | 6775.54 | -1.67 | *.09* |
| SLC vs. DCS: Pure (Letter) vs. Pure (Number) | 56.25 | 21.79 | 6775.65 | 2.58 | *.009* |
| DLC vs. DCS: Pure (Letter) vs. Mixed | -65.28 | 19.13 | 6775.47 | -3.41 | *.0006* |
| DLC vs. SLC: Pure (Letter) vs. Mixed | 3.50 | 19.11 | 6775.50 | 0.18 | .85 |
| SLC vs. DCS: Pure (Letter) vs. Mixed | 68.79 | 18.75 | 6775.71 | 3.67 | *.0002* |
| DLC vs. DCS: Pure (Number) vs. Mixed | 28.20 | 19.18 | 6775.25 | 1.47 | .14 |
| DLC vs. SLC: Pure (Number) vs. Mixed | 40.74 | 19.30 | 6775.42 | 2.11 | *.03* |
| SLC vs. DCS: Pure (Number) vs. Mixed | 12.54 | 18.85 | 6775.49 | 0.67 | .51 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | 34.20 | 30.68 | 6795.88 | 1.12 | .27 |
| DLC vs. DCS: Correct vs. Error | 36.65 | 27.70 | 6793.28 | 1.32 | .19 |
| SLC vs. DCS: Correct vs. Error | 2.45 | 28.71 | 6798.07 | 0.09 | .93 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 13745.0 | 117.24 |
| Display | (Intercept) | 1434.2 | 37.87 |
| Task | (Intercept) | 626.6 | 25.03 |
| Trial Type | (Intercept) | 3548.7 | 59.57 |
| Residual | | 45903.7 | 214.25 |

*Table 4.5.1: LMM results of RT analysis of overall performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

For the fixed effect of Language Context (LC), the differences between the groups was not significant, except between Dual LC group and Dense CSC group with an estimated difference of 76.71 *ms* (SE = 38.79, t = 1.98), with $p = .05$. Comparison between the groups showed Dual LC faster than Single LC and Dense CSC groups, whereas Single LC group was faster than Dense CSC group.

Regarding task condition, comparisons with Alternate task conditions showed statistical significance, for instance when comparing Alternate with Pure (Number) showed an estimated difference of 59.38 *ms* (SE = 14.70, $t = -4.04$), with $p < .001$, with a faster performance seen in Pure (Number) condition. Compared to all other task conditions, Alternate task condition showed slower performance, and this difference was statistically significant. Pure (Number) showed faster performance than Pure (Letter). Both, Pure (Letter) and Pure (Number) had faster performance than Mixed task condition.

Interactions between LC and task condition also revealed notable differences, particularly between DLC and SLC across certain task conditions. However, accuracy-related interactions did not reach significance.

*ANOVA*

ANOVA (Type III) was conducted using Satterthwaite's method to assess significance of the fixed effects, *(table 4.5.2)* of Language Context (LC), task condition (Condition), accuracy, and their interactions on reaction time performance. The main effect of LC was statistically significant, $F(2, 73.4) = 2.41$, $p = .09$, suggesting that differences between the levels of LC were significantly influential in the performance of the participants. There was a significant main effect of Condition, $F(3, 5838.4) = 39.39$, $p < .001$, indicating that task condition had a significant impact on the participants' performance. The main effect of Accuracy was not significant, $F(1, 6806.2) = 1.69$, $p = .19$, indicating that performance differences between correct and error trials were not statistically meaningful.

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 221671 | 110835 | 2 | 73.4 | 2.41 | *.09* |
| ***Condition*** | 5424265 | 1808088 | 3 | 5838.4 | 39.39 | *< .001* |
| ***Accuracy*** | 77772 | 77772 | 1 | 6806.2 | 1.69 | .19 |
| ***LC: Condition*** | 1229482 | 204914 | 6 | 6775.5 | 4.46 | *.0002* |
| ***LC: Accuracy*** | 91799 | 45900 | 2 | 6795.7 | 0.99 | .37 |

*Table 4.5.2: Type III Analysis of Variance Table with Satterthwaite's method of overall performance in univalent task.*

There was a significant interaction between LC and Condition, $F(6, 6775.5) = 4.46$, $p = .0002$, suggesting that the effect of LC on performance varied depending on the task condition. The interaction between LC and Accuracy was not significant, F(2, 6795.7) = 0.99, $p$ = .37, indicating no significant moderating effect of LC on the relationship between accuracy and performance.

In summary, the results indicate that LC and task condition individually, as well as their interaction play a significant role in shaping performance, while accuracy did not have a notable effect on performance or interact significantly with other factors.

### *Post HOC analysis*

To further understand group-wise comparison, a post HOC analysis of estimated marginal means (henceforth EMM) was performed.

*EM Means- Language Context*

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 908 | 54.3 | 2.59 | 719 | 1098 |
| ***Dual*** | 836 | 54.8 | 2.69 | 649 | 1022 |
| ***Dense*** | 915 | 53.9 | 2.51 | 723 | 1107 |

*Table 4.5.3: Group-wise EM Means based on Language Context of overall performance in univalent task.*

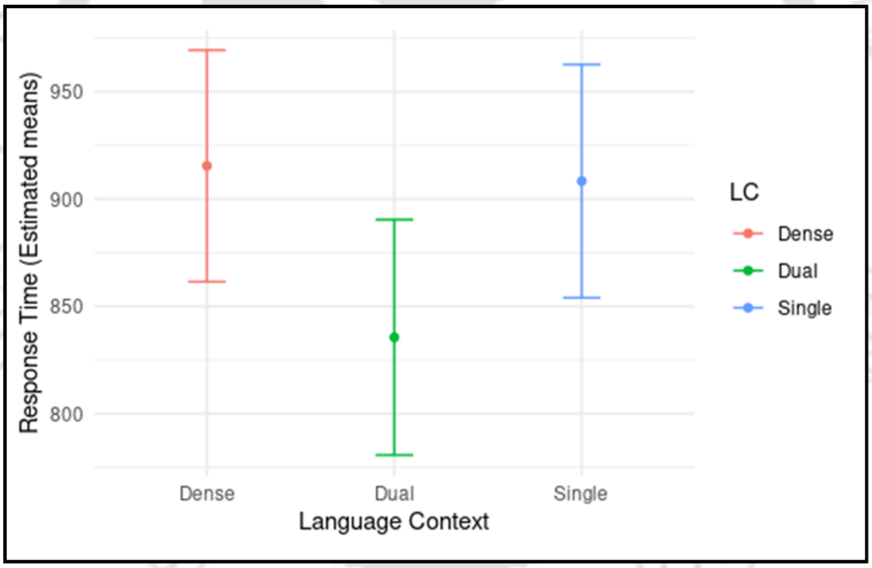


*Figure 4.5.3: Group-wise EM Means performance based on Language Context of overall performance in univalent task. Dual LC group shows the least EM means, followed by Single LC group, which is closely followed by Dense CSC group. Bars represent 95% confidence intervals.*

The estimated marginal means (EM means) for reaction times for different language context groups (LC) were analysed *(table 4.5.3)*. Dual LC group had the fastest performance, with a mean of 836 *ms* (SE = 54.8, df = 2.69, 95% CI [649, 1022]). Single LC group followed, with an EM mean of 908 *ms* (SE = 54.3, df = 2.59, 95% CI [719, 1098]). Finally, the Dense CSC group had the slowest mean performance, with a mean of 915 *ms* (SE = 53.9, df = 53.9, 95% CI [723, 1107]).

These results indicate that reaction times were somewhat similar across the Single and Dense conditions, with both conditions showing higher reaction times compared to the Dual condition. The overlapping confidence intervals suggest that while there may be differences in reaction times between these conditions, further statistical analysis would be required to determine if these differences are statistically significant *(see figure 4.5.3 for graphical representation)*.

*Pairwise analysis- Language Context*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -79.83 | 39.7 | 71.5 | -2.01 | .12 |
| ***Dense - Single*** | 7.08 | 39.0 | 73.6 | 0.18 | .98 |
| ***Dual - Single*** | -72.76 | 40.2 | 75.4 | -1.81 | .17 |

*Table 4.5.4: Pair-wise analysis based on Language context of overall performance in univalent task.*

To further analyse the differences, a pairwise comparison was conducted to evaluate differences in reaction times between the three LC groups *(table 4.5.4)*. Differences between none of the pairs showed statistical significance. When compared to Dense CSC group and Single LC groups, Dual showed a faster performance, however these differences were not statistically significant. The difference between the Dual LC and Dense CSC was an estimate of 79.83 *ms* (SE = 39.7, df = 71.5, t = -2.01), with *p* = .12, indicating no significant difference in reaction times between these two conditions. Similarly, the comparison between the Dual LC and Single LC was not significant, with an estimate of 72.76 *ms* (SE = 40.2, df = 75.4, t = -1.81), with *p* = .17. Additionally, no significant difference was found between the Dense CSC and Single LC groups, with an estimated difference of 7.08 *ms* (SE = 39.0, df = 73.6, t = 0.18), with *p* = .98.

Overall, these results indicate that the reaction times across the Dual, Dense, and Single conditions were relatively similar, with no statistically significant differences observed between any of the pairwise contrasts.

*EM Means- Task condition*

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Pure (Number)*** | 838 | 49.8 | 1.84 | 604 | 1071 |
| ***Pure (Letter)*** | 896 | 49.9 | 1.84 | 662 | 1129 |
| ***Alternate*** | 930 | 49.4 | 1.77 | 689 | 1170 |
| ***Mixed*** | 883 | 49.4 | 1.78 | 643 | 1123 |

*Table 4.5.5: Group-wise EM Means based on task condition of overall performance in univalent task.*

EM means for RTs across various task conditions were then analysed. Pure (Number) condition had an EM mean of 838 *ms* (SE = 49.8, df = 1.84, 95% CI [604, 1071]). This was followed by Mixed task condition with an EM mean of 883 *ms* (SE = 49.4, df = 1.78, 95% CI [643, 1123]). Pure (Letter) task condition showed a higher EM mean of 896 *ms* (SE = 49.9, df = 1.84, 95% CI

[662, 1129]). Finally, Alternate task condition had the highest EM mean at 930 *ms* (SE = 49.4, df = 1.77, 95% CI [689, 1170]).

These results suggest that reaction times were generally longest in the Alternate condition, followed by the Pure (Letter) and Mixed conditions, with the Pure (Number) condition showing the shortest reaction times. The overlapping confidence intervals indicate that while there are differences in EM means across conditions, further statistical analysis would be required to determine the significance of these differences *(see figure 4.5.4 for graphical representation)*.

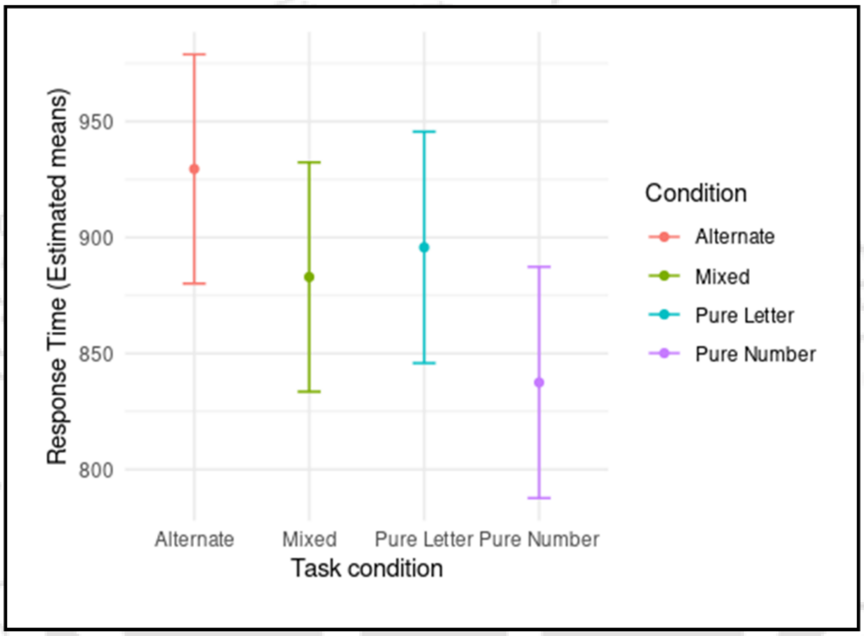


*Figure 4.5.4: Group-wise EM Means performance based on task condition of overall performance in univalent task. Performance in Pure (Number) task condition was the fastest, followed by Mixed condition, closely followed by Pure (Letter), and finally Alternate task condition. Bars represent 95% confidence intervals.*

*Pairwise analysis- Task condition*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Pure (Letter) - Pure (Number)*** | 58.2 | 11.23 | 4618 | 5.19 | *< .0001* |
| ***Alternate - Pure (Number)*** | 92.0 | 9.22 | 6438 | 9.98 | *< .0001* |
| ***Alternate - Pure (Letter)*** | 33.8 | 9.30 | 6302 | 3.64 | *.002* |
| ***Alternate - Mixed*** | 46.6 | 6.40 | 6791 | 7.27 | *< .0001* |
| ***Mixed - Pure (Number)*** | 45.5 | 9.29 | 6428 | 4.89 | *< .0001* |
| ***Mixed - Pure (Letter)*** | -12.8 | 9.37 | 6285 | -1.36 | .52 |

*Table 4.5.6: Pair-wise analysis based on task condition of overall performance in univalent task.*

A pairwise comparison analysis was conducted to evaluate differences in reaction times between the various task conditions *(table 4.5.6)*. The analysis revealed that RTs were significantly longer in the Pure (Letter) task condition compared to the Pure (Number) condition with an estimated difference of 58.2 *ms* (SE = 11.23, df = 4618, t = 5.19), where $p < .0001$. Similarly, reaction times in the Alternate condition were significantly longer than both, Pure (Number) condition, with an estimated difference of 92.0 *ms* (SE = 9.22, df = 6438, t = 9.98), with $p < .0001$; as well as Pure (Letter) condition, with an estimated difference of 33.8 *ms* (SE = 9.30, df = 6302, t = 3.64), with $p = .002$. Additionally, reaction times in the Alternate condition were significantly longer than in Mixed condition, with an estimated difference of 46.6 *ms* (SE = 6.40, df =6791, t = 7.27), where $p < .0001$. suggesting that participants took longer to respond in the Alternate condition, indicating that perhaps the Alternate task condition was more cognitively demanding.

Mixed task condition also showed significantly longer reaction times compared to the Pure (Number) condition with an estimated difference of 45.5 *ms* (SE = 9.29, df = 6428, t = 4.89), with $p < .0001$. However, the difference between the Mixed and Pure (Letter) conditions was not statistically significant, with an estimated difference of 12.8 *ms* (SE = 9.37, df = 6285, t = -1.36), with $p = .52$, indicating that these two conditions produced similar reaction times.

Overall, the results demonstrate that reaction times were generally longer in Alternate task condition compared to the other task conditions, with significant differences observed in most pairwise comparisons except for between Mixed and Pure (Letter) conditions.

*EM Means- LC * Condition*

| LC | Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Pure (Number)*** | 841 | 55.4 | 2.80 | 657 | 1025 |
| ***Single*** | ***Pure (Letter)*** | 949 | 55.4 | 2.80 | 765 | 1133 |
| ***Single*** | ***Alternate*** | 952 | 54.6 | 2.64 | 764 | 1140 |
| ***Single*** | ***Mixed*** | 892 | 54.6 | 2.65 | 704 | 1079 |
| ***Dual*** | ***Pure (Number)*** | 811 | 56.0 | 2.92 | 630 | 993 |
| ***Dual*** | ***Pure (Letter)*** | 826 | 56.0 | 2.93 | 645 | 1007 |
| ***Dual*** | ***Alternate*** | 871 | 55.1 | 2.74 | 686 | 1056 |
| ***Dual*** | ***Mixed*** | 834 | 55.2 | 2.75 | 649 | 1019 |
| ***Dense*** | ***Pure (Number)*** | 860 | 55.0 | 2.72 | 675 | 1046 |
| ***Dense*** | ***Pure (Letter)*** | 912 | 55.0 | 2.72 | 727 | 1098 |
| ***Dense*** | ***Alternate*** | 966 | 54.2 | 2.57 | 776 | 1156 |
| ***Dense*** | ***Mixed*** | 923 | 54.2 | 2.57 | 733 | 1113 |

*Table 4.5.7: Group-wise EM Means based on interaction between LC and task condition of overall performance in univalent task.*

An EM means analysis was performed to see the interaction between LC groups and their performance in the various task conditions *(table 4.5.7)*.

In Pure (Number) task condition, Dual LC group had the fastest performance with an estimated mean of 811 *ms* (SE = 56.0, df = 2.92, 95% CI [630, 993]). This was followed by Single LC group with an estimated mean of 841 *ms* (SE = 55.4, df = 2.80, 95% CI [657, 1025]). Finally came the Dense CSC group, with an estimated mean of 860 *ms* (SE = 55.0, df = 2.72, 95% CI [675, 1046]).

In Pure (Letter) task condition, Dual LC had the least EM means of 826 *ms* (SE = 56.0, df = 2.93, 95% CI [645, 1007]). Dense CSC group came next, with an estimate of 912 *ms* (SE = 55.0, df =

2.72, 95% CI [727, 1098]). Single LC group had the slowest performance in this task condition with an estimated mean of 949 *ms* (SE = 55.4, df = 2.80, 95% CI [765, 1133]).

In Alternate task condition, Dual LC group had the fastest performance, with an estimate of 871 *ms* (SE = 55.1, df = 2.74, 95% CI [686, 1056]). Single LC group came next, with an estimated mean of 952 *ms* (SE = 54.6, df = 2.64, 95% CI [764, 1140]). Dense CSC group followed with an estimated mean of 966 *ms* (SE = 54.2, df = 2.57, 95% CI [776, 1156]).

In Mixed task condition, Dual LC group had the least EM means of 834 *ms* (SE = 55.2, df = 2.75, 95% CI [649, 1019]). Single LC group had an estimated mean of 892 *ms* (SE = 54.6, df = 2.65, 95% CI [704, 1079]). Dense CSC group were the slowest, with an estimated mean of 923 *ms* (SE = 54.2, df = 2.57, 95% CI [733, 1113]).

These results suggest that reaction times tend to increase with higher task complexity (Alternate and Mixed conditions). Reaction times were generally highest in the Dense CSC across all conditions, particularly in the Alternate condition. Conversely, reaction times were shorter in the Dual LSC across all conditions, with the Pure (Number) condition showing the shortest reaction times overall. These findings suggest that both task condition and letter set complexity significantly influence reaction times *(see figure 4.5.5 for graphical representation)*.

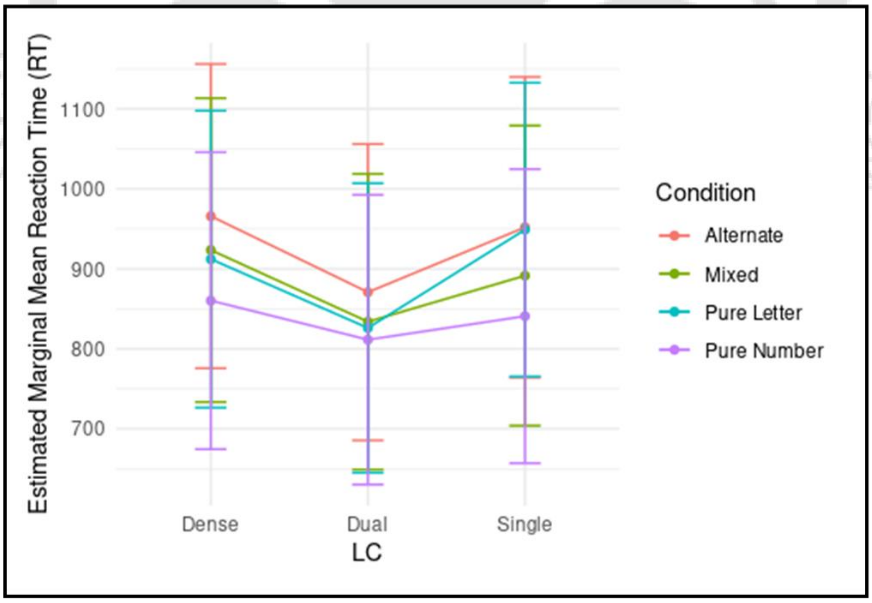


*Figure 4.5.5: Interaction of LC × Task condition of overall performance in univalent task.*

### *Accuracy analysis*

*Error rate.* Error-rate analysis revealed that Single LC group had the least errors (4.35%), followed by Dual LC group (5.22%), and then came Dense CSC group (6.86%).

*GLMM.* A generalized linear mixed-effects model (GLMM) was conducted to predict accuracy based on language context (LC), task condition (Condition), and scaled reaction time, with random intercepts for subjects and trial types. The model used a binomial distribution and included an interaction between LC and Condition.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -2.84 | 0.34 | -8.33 | < *.001* |
| ***LC*** | | | | |
| DLC vs. DCS | 0.14 | 0.33 | 0.42 | .67 |
| DLC vs. SLC | -0.40 | 0.34 | -1.16 | .25 |
| SLC vs. DCS | 0.54 | 0.33 | 1.61 | .11 |
| ***Task condition*** | | | | |
| Alternate vs. Pure (Letter) | -0.63 | 0.36 | -1.77 | *.08* |
| Alternate vs. Pure (Number) | -0.04 | 0.30 | -0.14 | .89 |
| Alternate vs. Mixed | -0.47 | 0.22 | -2.08 | *.04* |
| Pure (Letter) vs. Pure (Number) | 0.59 | 0.40 | 1.48 | .14 |
| Pure (Letter) vs. Mixed | 0.17 | 0.37 | 0.45 | .65 |
| Pure (Number) vs. Mixed | -0.42 | 0.31 | -1.36 | .18 |
| ***Response time*** | | | | |
| RT (scaled) | 0.02 | 0.06 | 0.27 | .79 |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Alternate vs. Pure (Letter) | 0.66 | 0.46 | 1.43 | .15 |
| DLC vs. DCS: Alternate vs. Pure (Letter) | 0.40 | 0.44 | 0.90 | .37 |
| SLC vs. DCS: Alternate vs. Pure (Letter) | -0.26 | 0.40 | -0.64 | .52 |
| DLC vs. SLC: Alternate vs. Pure (Number) | 0.006 | 0.42 | 0.015 | .99 |
| DLC vs. DCS: Alternate vs. Pure (Number) | 0.08 | 0.38 | 0.20 | .84 |
| SLC vs. DCS: Alternate vs. Pure (Number) | 0.07 | 0.40 | 0.18 | .86 |
| DLC vs. SLC: Alternate vs. Mixed | 0.06 | 0.33 | 0.17 | .86 |
| DLC vs. DCS: Alternate vs. Mixed | 0.23 | 0.30 | 0.77 | .44 |
| SLC vs. DCS: Alternate vs. Mixed | 0.17 | 0.31 | 0.55 | .58 |
| DLC vs. DCS: Pure (Letter) vs. Pure (Number) | -0.65 | 0.54 | -1.20 | .23 |
| DLC vs. SLC: Pure (Letter) vs. Pure (Number) | -0.32 | 0.51 | -0.63 | .53 |
| SLC vs. DCS: Pure (Letter) vs. Pure (Number) | 0.33 | 0.48 | 0.68 | .50 |
| DLC vs. DCS: Pure (Letter) vs. Mixed | -0.60 | 0.48 | -1.26 | .21 |
| DLC vs. SLC: Pure (Letter) vs. Mixed | -0.17 | 0.45 | -0.37 | .71 |
| SLC vs. DCS: Pure (Letter) vs. Mixed | 0.43 | 0.42 | 1.04 | .30 |
| DLC vs. DCS: Pure (Number) vs. Mixed | 0.05 | 0.44 | 0.12 | .91 |
| DLC vs. SLC: Pure (Number) vs. Mixed | 0.15 | 0.40 | 0.39 | .70 |
| SLC vs. DCS: Pure (Number) vs. Mixed | 0.10 | 0.41 | 0.25 | .81 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.66 | 0.81 |
| Trial Type | (Intercept) | 0.12 | 0.34 |

*Table 4.5.8: GLMM results of error analysis of overall performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

The random effects revealed variability across both subjects and trial types. Specifically, the variance associated with the random intercept for subjects was 0.66 (SD = 0.81), indicating moderate variability in accuracy between subjects. The variance for trial type was smaller, at 0.12 (SD = 0.34), suggesting relatively low variability across trial types.

The main effect of LC was not significant for any comparisons, with $p > 0.1$ when comparing the three LC groups, indicating no significant differences in accuracy between the language context groups. Differences between the levels showed Dual LC group had fewer errors than Dense CSC group, and Single LC group had lesser errors than Dual LC group and Dense CSC group.

For task condition, the comparison between Alternate and Mixed conditions showed significantly lower accuracy compared to the Mixed condition with an estimated difference of 0.47 (SE = 0.22, z = -2.08), with $p = .04$, suggesting that participants had more errors in the Alternate task compared to the Mixed task. However, the comparison between the other levels of task condition were not significant. Results showed that performance in other task conditions had greater accuracy than Alternate task condition. Pure (Letter) had higher accuracy than Pure (Number) and Mixed task conditions. Mixed condition had higher accuracy, however, than Pure (Number).

Response time did not have a significant effect on accuracy, with an estimate of 0.02 (SE = 0.06, z = 0.27), with $p = .79$, indicating that variations in response time were not predictive of accuracy. The interaction between LC and task condition was not significant in any comparison.

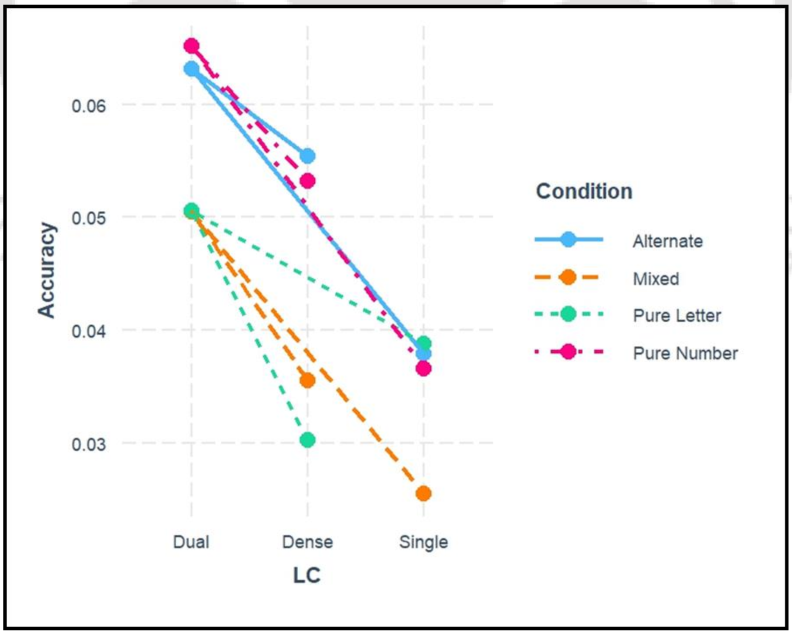


*Figure 4.5.6: Graph showing error analysis of overall performance in univalent task. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

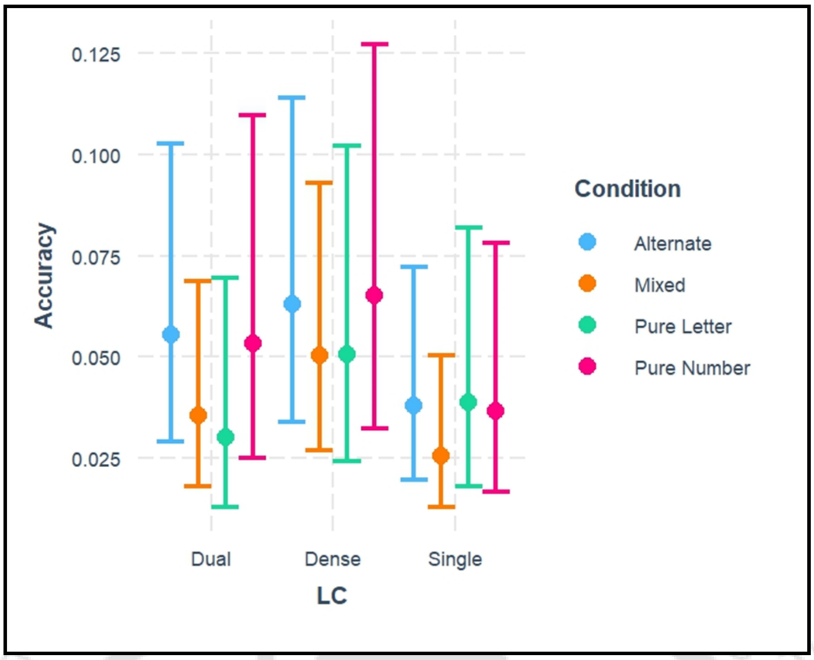


*Figure 4.5.7: Error analysis of each LC group in overall performance in univalent task. Each coloured bar represents a different task condition.*

To summarize, the results indicate that task condition plays a significant role in predicting accuracy, particularly when comparing the Alternate task condition with Mixed and Pure (Letter) conditions, with the Alternate condition showing reduced accuracy *(see figure 4.5.6, 4.5.7 for graphical representation)*. However, no significant effects were found for LC, response time, or their interactions with task condition, suggesting that these variables did not substantially impact performance.

### *Post-error analysis*

A linear mixed-effects model was conducted to analyse reaction time (RT) based on post-error status, language context (LC), task condition (Condition), and their interactions. Random effects included random intercepts and slopes for post-error status across participants and random intercepts for trial types.

The random effects analysis indicated substantial variability between participants (Variance = 13,522, SD = 116.29), trial types (Variance = 3,897, SD = 62.43) and Post-Error (Variance = 2,638, SD = 51.36). The residual variance was 47,052 (SD = 216.91), reflecting the remaining unexplained variability in reaction times. A correlation of -0.05 is close to zero, indicating a very weak relationship. This suggests that subjects with higher average RTs (random intercepts) do not exhibit larger or smaller post-error effects (random slope).

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 891.33 | 51.94 | 1.89 | 17.16 | *.004* |
| Post error | 50.61 | 28.74 | 67.21 | 1.76 | *.08* |
| ***LC*** | | | | | |
| DLC vs. DCS | 64.17 | 37.42 | 57.99 | 1.72 | *.09* |
| DLC vs. SLC | 55.73 | 37.41 | 57.93 | 1.49 | .14 |
| SLC vs. DCS | 8.44 | 36.48 | 58.04 | 0.23 | .82 |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Letter) | -53.85 | 8.72 | 6749.04 | -6.18 | *< .001* |
| Alternate vs. Pure (Number) | -75.11 | 8.77 | 6747.74 | -8.57 | *< .001* |
| Alternate vs. Mixed | -46.66 | 6.60 | 6753.05 | -7.07 | *< .001* |
| Pure (Letter) vs. Pure (Number) | -21.26 | 9.35 | 6753.59 | -2.27 | *.02* |
| Pure (Letter) vs. Mixed | 7.19 | 8.71 | 6747.30 | 0.83 | .41 |
| Pure (Number) vs. Mixed | 28.45 | 8.76 | 6745.85 | 3.25 | *.001* |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. DCS | 21.70 | 37.07 | 45.14 | 0.59 | .56 |
| Post error: DLC vs. SLC | 29.19 | 33.75 | 38.99 | 0.87 | .39 |
| Post error: SLC vs. DCS | 7.48 | 34.95 | 39.92 | 0.21 | .83 |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Alternate vs. Pure (Letter) | 32.79 | 36.63 | 4069.71 | 0.90 | .37 |
| Post error: Alternate vs. Pure (Number) | 98.99 | 36.20 | 3662.31 | 2.74 | *.0006* |
| Post error: Alternate vs. Mixed | 27.31 | 27.79 | 5061.26 | 0.08 | .33 |
| Post error: Pure (Letter) vs. Pure (Number) | 66.20 | 44.68 | 3147.41 | 1.48 | .14 |
| Post error: Pure (Letter) vs. Mixed | -5.48 | 38.01 | 4188.63 | -0.14 | .89 |
| Post error: Pure (Number) vs. Mixed | -71.68 | 37.50 | 4269.53 | -1.91 | *.06* |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Corr** |
| Subject | (Intercept) | 13522 | 116.29 | |
| | Post Error | 2638 | 51.36 | -0.05 |
| Trial Type | (Intercept) | 3897 | 62.43 | |
| Residual | | 47052 | 216.91 | |

*Table 4.5.9: LMM results of post-error performance of overall performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

Post-error performance had a significant effect on reaction time with an estimate of 50.61 (SE = 28.74, t = 1.76), with $p = .08$, suggesting a tendency for increased reaction times following errors, though this effect did not reach conventional significance levels.

Interactions between post-error status and LC were not significant, indicating no significant moderation of the post-error effect by language context. Analysis showed that performance of Dual LC group in post-error performance was slower than both, Single LC group and Dense CSC group. Single LC group showed slower performance than Dense CSC group. However, these differences among the LC groups were not statistically significant.

For task condition, the interaction between post-error status and condition showed a significant effect only for some levels. For instance, when comparing performance between Alternate task condition and Pure (Number) condition, there was an estimated difference of 98.99 *ms* (SE = 36.20, t = 2.74), with *p* = .0006, where post-error performance in Pure (Number) was faster than Alternate condition. Alternate task condition also showed slower performance than Pure (Letter) as well as Mixed conditions, but these differences were not statistically significant. Mixed task condition showed slower post-error performance than Pure (Letter) and Pure (Number) conditions, and Pure (Number) in turn showed faster performance than Pure (Letter) condition.

In summary, the results indicate that the interactions between post-error status and LC or task conditions were generally not significant, suggesting that these interactions do not substantially alter the effect of post-error status on reaction time.

### *Local Switch Cost*

Local switch cost is the difference in performance between Switch and Repeat trials in the Mixed block. This study has also included the Alternate task condition to observe the local switch cost.

### *RT analysis*

*Linear Mixed-Model Analysis*

Language Context (LC), Trial Type, and Accuracy were the fixed effects. There were 3 levels in LC (Single, Dual and Dense code switching), 4 levels in Trial Type (Repeat A, Mixed A, Repeat M, Mixed M), whereas Accuracy had 2 levels (Correct and Error). The random effects were Subject, Display, Task, and Condition.

The random effects for subject, display, task, and condition indicated significant variability across these factors. The variance associated with subject was 14,399.7 (SD = 120.00), suggesting considerable individual differences in response times. Display had a variance of 1,528.2 (SD = 39.09), indicating moderate variability in response times across different display conditions. The task variance was 657.2 (SD = 25.64), and condition variance was 460.8 (SD = 21.47), both suggesting smaller but non-negligible variability in response times across these factors. The residual variance was 46,661.8 (SD = 216.01), representing the within-subject variability.

For the fixed effect of Language Context (LC), the comparison between the Dual LC group (DLC) and Dense CSC group (DCS) was significant, with the performance in Dual LC faster than Dense CSC group with an estimated difference of 80.91 *ms* (SE = 41.16, df = 73.39, t = 1.97), with *p* = .05. However, the other comparisons were not statistically significant where Dual LC group showed faster performance than Single LC group, and Single LC group showed faster performance than Dense CSC group.

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 841.23 | 42.06 | 16.40 | 20.00 | < *.001* |
| ***LC*** | | | | | |
| DLC vs. DCS | 80.91 | 41.16 | 73.39 | 1.97 | *.05* |
| DLC vs. SLC | 64.98 | 41.13 | 73.22 | 1.58 | .12 |
| SLC vs. DCS | 15.94 | 40.14 | 73.58 | 0.40 | .69 |
| ***Trial type*** | | | | | |
| Repeat A vs Repeat M | -11.06 | 34.45 | 4544.66 | -0.32 | .75 |
| Repeat A vs. Switch A | 100.95 | 16.77 | 4346.16 | 6.02 | < *.001* |
| Repeat M vs. Switch M | 49.92 | 16.41 | 4477.93 | 3.04 | *.002* |
| Switch A vs. Switch M | -62.09 | 35.99 | 4544.09 | -1.73 | *.08* |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -33.98 | 24.56 | 4562.51 | -1.38 | .17 |
| ***LC x Trial type interaction*** | | | | | |
| DLC vs. SLC: Repeat A vs. Repeat M | -21.93 | 22.43 | 4539.59 | -0.98 | .33 |
| DLC vs. DCS: Repeat A vs. Repeat M | -45.80 | 22.34 | 4539.86 | -2.05 | *.04* |
| SLC vs. DCS: Repeat A vs Repeat M | 23.86 | 21.99 | 4539.60 | 1.09 | .28 |
| DLC vs. SLC: Repeat A vs. Switch A | 6.37 | 22.30 | 4539.87 | 0.29 | .78 |
| DLC vs. DCS: Repeat A vs. Switch A | -8.16 | 22.30 | 4539.67 | -0.36 | .71 |
| SLC vs. DCS: Repeat A vs. Switch A | -14.53 | 22.02 | 4540.12 | -0.66 | .61 |
| DLC vs. DCS: Repeat M vs. Switch M | 41.10 | 22.03 | 4539.64 | 1.87 | *.06* |
| DLC vs. SLC: Repeat M vs. Switch M | 34.55 | 22.09 | 4539.55 | 1.56 | .12 |
| SLC vs. DCS: Repeat M vs. Switch M | -6.56 | 21.68 | 4539.74 | -0.30 | .76 |
| DLC vs. DCS: Switch A vs. Switch M | -11.06 | 21.96 | 4539.82 | -0.50 | .61 |
| DLC vs. SLC: Switch A vs. Switch M | 20.78 | 21.91 | 4539.70 | 0.95 | .34 |
| SLC vs. DCS: Switch A vs. Switch M | 31.84 | 21.64 | 4540.46 | 1.47 | .14 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | 45.74 | 36.50 | 4564.94 | 1.25 | .21 |
| DLC vs. DCS: Correct vs. Error | 44.23 | 32.65 | 4562.49 | 1.36 | .18 |
| SLC vs. DCS: Correct vs. Error | -1.51 | 34.52 | 4564.73 | -0.04 | .97 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 14399.7 | 120.00 |
| Display | (Intercept) | 1528.2 | 39.09 |
| Task | (Intercept) | 657.2 | 25.64 |
| Condition | (Intercept) | 460.8 | 21.47 |
| Residual | | 46661.8 | 216.01 |

*Table 4.5.10: LMM results of RT analysis of local switch cost performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context; A: Alternate task block; M: Mixed task block).*

For the fixed effect of trial type, the comparison between Repeat A and Switch A was highly significant with an estimated difference of 100.95 *ms* (SE = 16.77, df = 4346.16, t = 6.02), with $p < .001$, showing that participants had significantly shorter RTs in Repeat trial type in Alternate task condition compared to Switch trial type in Alternate task condition. Comparison between other levels showed that performance in Mixed trials were faster than that in Alternate trials, and performance in Repeat trials were faster than Switch trials.

The accuracy effect (Correct vs. Error) was not statistically significant with an estimate of 33.98 *ms* (SE = 24.56, df = 4562.51, t = -1.38), with $p$ = .17, indicating that there was no significant difference in the RTs between correct and error trials. Further analysis was done to examine finer details of the accuracy-related performance of the participants.

The interaction between LC and trial type showed a significant effect only for the comparison between DLC vs. DCS in the Repeat A vs. Repeat M condition with an estimated difference of 45.80 *ms* (SE = 22.34, df = 4539.86, t = -2.05), with p = .04, suggesting that the effect of trial type on RT differed significantly between DLC and DCS. Other interactions between LC and trial type were not significant, indicating no significant differences in response times across other conditions.

The interaction between LC and accuracy similarly did not show significant effects, suggesting that the relationship between language context and accuracy did not significantly impact RT.

In summary, the LMM analysis revealed significant main effects for trial type, with longer reaction times in the Switch A condition compared to Repeat A. A marginal effect was found for LC, where DCS participants tended to have slower RTs than DLC. A significant interaction between LC and trial type was observed for DLC vs. DCS in the Repeat A vs. Repeat M condition. However, no significant effects were found for accuracy or its interactions with LC.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 287633 | 143817 | 2 | 77.6 | 3.08 | *.05* |
| ***Trial Type*** | 6330970 | 2110323 | 3 | 3793.1 | 45.23 | *< .001* |
| ***Accuracy*** | 3661 | 3661 | 1 | 4574.9 | 0.08 | .78 |
| ***LC: Trial Type*** | 401259 | 66877 | 6 | 4539.8 | 1.43 | .20 |
| ***LC: Accuracy*** | 105836 | 52918 | 2 | 4563.9 | 1.13 | .32 |

*Table 4.5.11: Type III Analysis of Variance Table with Satterthwaite's method groups of local switch cost performance in univalent task.*

A Type III ANOVA was conducted to examine the effects of language context (LC), trial type, and accuracy on the dependent variable, RT, as well as their interactions *(table 4.5.11)*. The main effect of Language Context (LC) was significant, with $F(2, 77.6) = 3.08$, $p = .05$, indicating that LC had a significant effect on participants' RT. The main effect of trial type was highly significant, $F(3, 3793.1) = 45.23$, $p < .001$, suggesting substantial differences in RTs across different trial types. However, the main effect of accuracy was not significant, $F(1, 4574.9) = 0.08$, $p = .78$, indicating no meaningful effect of accuracy on response times.

The interaction between LC and trial type was not significant, $F(6, 4539.8) = 1.43$, $p = .20$, suggesting that the effect of LC on response times did not vary significantly across different trial types. Similarly, the interaction between LC and accuracy was also not significant, $F(2, 4563.9) = 1.13$, $p = .32$, indicating that the effect of LC did not differ depending on accuracy levels.

### *Post-HOC analysis*

An EM Means analysis as well as pairwise analysis was performed on the RTs based on Language Context, Trial Type, and their interaction.

*EM Means- Language context*

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 933 | 38.9 | 12.1 | 849 | 1018 |
| ***Dual*** | 856 | 39.4 | 12.6 | 771 | 942 |
| ***Dense*** | 955 | 38.0 | 11.1 | 871 | 1039 |

*Table 4.5.12: Group-wise EM Means based on Language Context of local switch cost performance in univalent task.*

Estimated marginal means (EM means) were calculated for the effect of Language Context (LC) on response times *(table 4.5.12)*. Participants in Dual LC had an estimated mean RT of 856 *ms* (SE = 39.4, df = 12.6, 95% CI [771, 942]). Participants in the Single LC had an estimated mean response time of 933 *ms* (SE = 38.9, df = 12.1, 95% CI [849, 1018]), while participants in the Dense condition had an estimated mean response time of 955 *ms* (SE = 38.0, df = 11.1, 95% CI [871, 1039]). These results suggest variability in response times across different levels of LC, with the Dual LC group showing the fastest response times, followed by Single LC group and then Dense CSC group *(see figure 4.5.8 for graphical representation)*.

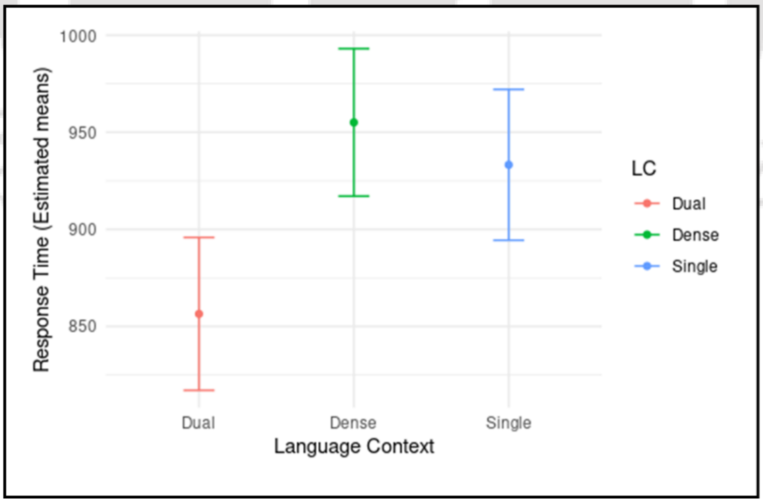


*Figure 4.5.8: Group-wise EM Means performance based on Language Context of local switch cost performance in univalent task. Dual LC group shows the least EM means, followed by Single LC group, and then Dense CSC group. Bars represent 95% confidence intervals.*

*Pairwise analysis- Language context*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -98.7 | 41.3 | 74.5 | -2.39 | *.05* |
| ***Dense - Single*** | 21.8 | 40.8 | 78.4 | 0.54 | .85 |
| ***Dual - Single*** | -76.8 | 42.1 | 80.2 | -1.83 | .17 |

*Table 4.5.13: Pair-wise analysis based on Language context of local switch cost performance in univalent task.*

A pairwise comparison analysis was conducted to examine differences in performance among the difference LC groups *(table 4.5.13)*. Dual LC group showed a significantly faster performance compared to the Dense condition, with an estimated difference of 98.7 *ms* (SE = 41.3, df = 74.5, t = -2.39), with $p$ = .05. However, the difference between the Dense CSC and Single LC groups was not significant, with an estimated difference of 21.8 *ms* (SE = 40.8, df = 78.4, t = 0.54), with $p$ = .85. Similarly, the difference between the Dual LC and Single LC groups was not significant, with an estimated difference of 76.8 *ms* (SE = 42.1, df = 80.2, t = -1.83), with $p$ = .17. These results suggest that while Dual LC group was significantly faster than the Dense CSC group, no significant differences were found between the Dense CSC and Single LC groups or Dual LC and Single LC groups.

*EM Means- Trial Type*

| Trial Type | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Repeat A*** | 888 | 34.6 | 7.95 | 808 | 968 |
| ***Repeat M*** | 854 | 34.7 | 8.00 | 774 | 934 |
| ***Switch A*** | 988 | 34.6 | 7.89 | 908 | 1068 |
| ***Switch M*** | 929 | 34.5 | 7.86 | 849 | 1009 |

*Table 4.5.14: Group-wise EM Means based on trial type of local switch cost performance in univalent task. (A: Alternate task condition; M: Mixed task condition).*

Estimated marginal means (EM means) for response times were calculated for different trial types. Performance in Repeat M trials was the fastest, with an estimated mean of 854 *ms* (SE = 34.7, df = 8.0, 95% CI [774, 934]). For the Repeat A trials, the estimated mean response time was 888 *ms* (SE = 34.6, df = 7.95, 95% CI [808, 968]). While the Switch M trials showed an estimated mean of 929 *ms* (SE = 34.5, df = 7.86, 95% CI [849, 1009]), the Switch A trials had the highest estimated mean response time of 988 *ms* (SE = 34.6, df = 7.89, 95% CI [908, 1068]). These results indicate that switch trials in both task conditions had slower mean RT as compared to the Repeat trials *(see figure 4.5.9 for graphical representation)*.

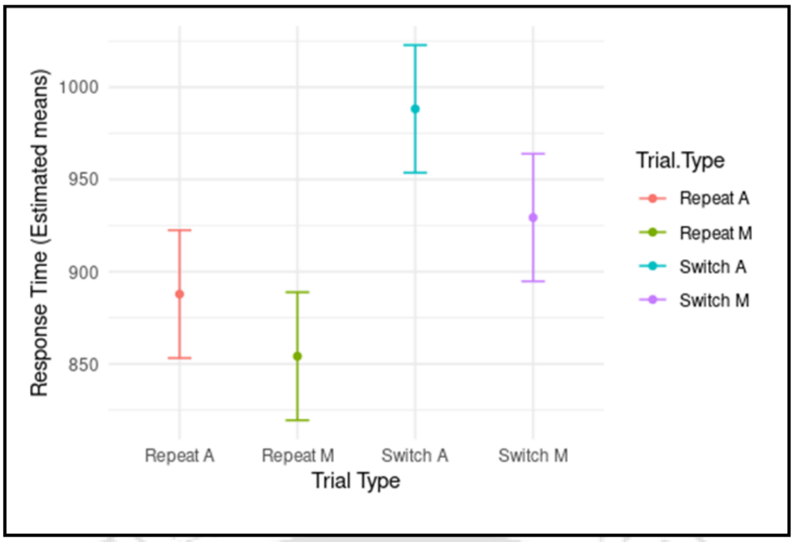


*Figure 4.5.9: Group-wise EM Means performance based on trial type of local switch cost performance in univalent task. Performance in Repeat trials in Mixed condition was the fastest, followed by Repeat trials in Alternate task block, then Switch trials of Mixed conditions and finally Switch trials in Alternate block. Bars represent 95% confidence intervals. (A: Alternate task condition; M: Mixed task condition).*

*Pairwise analysis- Trial Type*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Repeat A - Repeat M*** | 33.6 | 31.79 | 585175 | 1.06 | .72 |
| ***Repeat A - Switch A*** | -100.4 | 10.47 | 3149 | -9.59 | < *.0001* |
| ***Repeat M - Switch M*** | -75.1 | 9.93 | 3728 | -7.57 | < *.0001* |
| ***Switch A - Switch M*** | 58.9 | 31.73 | 632052 | 1.86 | .25 |

*Table 4.5.15: Table with pair-wise analysis based on trial type of local switch cost performance in univalent task. (A: Alternate task condition; M: Mixed task condition).*

A pairwise comparison analysis was conducted to examine differences in response times between the trial types *(table 4.5.15)*. A significant difference was found between Repeat A and Switch A trials, with Switch A trials being significantly slower by 100.4 *ms* (SE = 10.47, df = 3149, t = -9.59), with $p < .0001$. Similarly, Repeat M trials were significantly faster than Switch M trials by 75.1 *ms* (SE = 9.93, df = 3728, t = -7.57), $p < .0001$. However, there was no significant difference in performances between Repeat A and Repeat M trials, with an estimated difference of 33.6 *ms* (SE = 31.79, df = 585175, t = 1.06), with $p = .72$. The difference between Switch A and Switch M trials was also not significant, with an estimated difference of 58.9 *ms* (SE = 31.73, df = 632052, t = 1.86), $p = .25$. These findings indicate that switch trials were generally slower than repeat trials, in both Alternate and Mixed task conditions.

*EM Means- LC * Trial Type*

| LC | Trial Type | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Repeat A*** | 912 | 42.9 | 18.0 | 822 | 1002 |
| ***Single*** | ***Switch A*** | 1019 | 42.7 | 17.6 | 930 | 1109 |
| ***Single*** | ***Repeat M*** | 855 | 43.0 | 18.2 | 765 | 946 |
| ***Single*** | ***Switch M*** | 946 | 42.7 | 17.7 | 856 | 1036 |
| ***Dual*** | ***Repeat A*** | 824 | 43.4 | 18.7 | 733 | 915 |
| ***Dual*** | ***Switch A*** | 925 | 43.2 | 18.4 | 834 | 1016 |
| ***Dual*** | ***Repeat M*** | 813 | 43.6 | 18.9 | 722 | 904 |
| ***Dual*** | ***Switch M*** | 863 | 43.3 | 18.4 | 772 | 954 |
| ***Dense*** | ***Repeat A*** | 927 | 42.2 | 16.8 | 838 | 1016 |
| ***Dense*** | ***Switch A*** | 1020 | 41.9 | 16.4 | 931 | 1109 |
| ***Dense*** | ***Repeat M*** | 894 | 42.3 | 16.9 | 805 | 983 |
| ***Dense*** | ***Switch M*** | 979 | 41.9 | 16.4 | 890 | 1067 |

*Table 4.5.16: Table with group-wise EM Means based on interaction between LC and trial type of local switch cost performance in univalent task. (A: Alternate task condition; M: Mixed task condition).*

A mixed-effects model estimated the mean response times (RTs) for different levels of Local Cost (LC) across four trial types: Repeat A, Switch A, Repeat M, and Switch M.

For Repeat trials in Alternate task block, Dual LC group had the fastest performance, with an estimated mean of 824 *ms* (SE = 43.4, df = 18.7, 95% CI [733, 915]). Single LC group followed with an estimated mean of 912 (SE = 42.9, df = 18,0, 95% CI [822, 1002]). Finally, there was the Dense CSC group with an estimated mean of 927 *ms* (SE = 42.2, df = 16.8, 95% CI [838, 1016]).

For Switch trials in Alternate block, Dual LC group had the least EM mean of 925 (SE = 43.2, df = 18.4, 95% CI [834, 1016]). Single LC group came next with an estimated mean of 1019 *ms* (SE = 42.7, df = 17.6, 95% CI [930, 1109]). They were closely followed by the Dense CSC group with an estimated mean of 1020 *ms* (SE = 41.9, df = 16.4 95% CI [931, 1109]).

In the Repeat trials of Mixed task block, Dual LC group had the least mean RT of 813 *ms* (SE = 43.6, df = 18.9, 95% CI [722, 904]). They were followed by Single LC group with an estimated mean of 855 *ms* (SE = 43.0, df = 18.2, 95% CI [765, 946]). Dense CSC group had the highest mean RT of 894 *ms* (SE = 42.3, df = 16.9, 95% CI [805, 983]).

In the Switch trials of Mixed task block, Dual LC group outperformed the other groups with an estimated mean of 863 *ms* (SE = 43.3, df = 18.4, 95% CI [772, 954]). They were followed by Single LC group with an estimated mean of 946 *ms* (SE = 42.7, df = 17.7, 95% CI [856, 1036]). Dense CSC had an estimated mean of 979 *ms* (SE = 41.9, df = 16.4, 95% CI [890, 1067]).

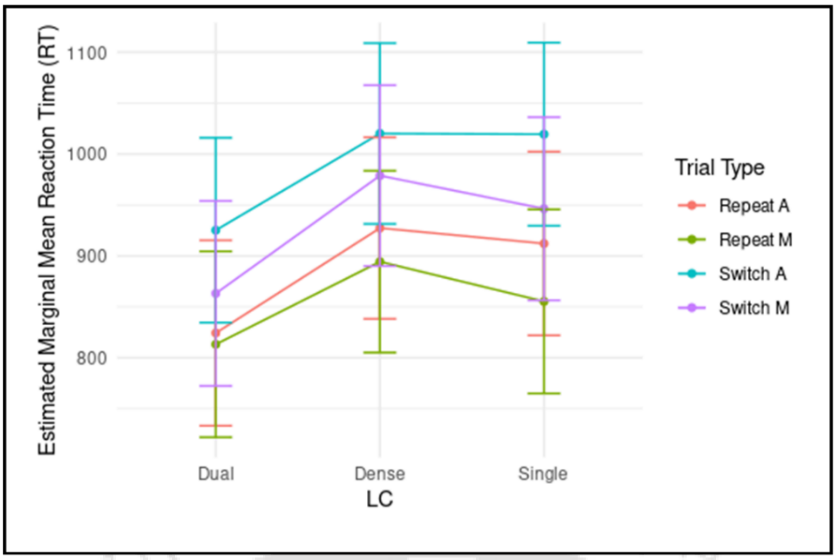


*Figure 4.5.10: Interaction of LC × Task condition of local switch cost performance in univalent task. (A: Alternate task condition; M: Mixed task condition).*

Overall, the Switch trials had longer response times than Repeat trials across all LC levels, with the performance of all groups generally slowest in Switch trials in Alternate task condition, and fastest in Repeat trials of Mixed task condition *(see figure 4.5.10 for graphical representation)*. The Dual LC group had fastest performance across all trial types, followed by Single LC group and then the Dense CSC group. These results suggest that both trial type and the local cost condition significantly influence response times, with Switch trials generally slower than Repeat trials across all conditions.

***Accuracy analysis***

*Error rate.* Error-rate analysis revealed that Single LC group had the least errors (4.56%), followed by Dual LC group (5.88%), and then came Dense CSC group (7.44%).

*GLMM.* A generalized linear mixed model (GLMM) was conducted to examine the effects of Language Context (LC) and trial type on accuracy, while controlling for response time (RT) and interactions between LC and trial type. The random effects revealed that the variance due to Subject was 0.64 (SD = 0.80), while the variance for Condition was 0, indicating no variability across conditions.

For the fixed effect of LC, no significant effects were observed. Dual LC group had more errors than Single LC group and Dense CSC group. Dense CSC group had more errors than Single LC group.

Similarly, Trial Type contrasts also did not reach significance. Repeat trials showed lesser errors than Switch trials. Trials in Mixed condition had lesser errors than Alternate task condition. The effect of scaled response time (RT) was also non-significant. In terms of interaction effects between LC and trial type, none of the interactions were significant.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -3.03 | 0.30 | -10.19 | < *.001* |
| ***LC*** | | | | |
| DLC vs. DCS | -0.27 | 0.42 | -0.63 | .53 |
| DLC vs. SLC | -0.66 | 0.45 | -1.47 | .14 |
| SLC vs. DCS | 0.39 | 0.45 | 0.86 | .39 |
| ***Trial type*** | | | | |
| Repeat A vs Repeat M | -0.56 | 0.37 | -1.53 | .13 |
| Repeat A vs. Switch A | 0.41 | 0.29 | 1.37 | .17 |
| Repeat M vs. Switch M | 0.58 | 0.36 | 1.61 | .11 |
| Switch A vs. Switch M | -0.38 | 0.29 | -1.35 | .18 |
| ***Response time*** | | | | |
| RT (scaled) | 0.08 | 0.07 | 1.72 | .24 |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Repeat A vs Repeat M | 0.28 | 0.56 | 0.50 | .62 |
| DLC vs. DCS: Repeat A vs Repeat M | 0.66 | 0.50 | 1.33 | .19 |
| SLC vs. DCS: Repeat A vs Repeat M | 0.38 | 0.54 | 0.70 | .48 |
| DLC vs. SLC: Repeat A vs. Switch A | 0.47 | 0.45 | 1.04 | .30 |
| DLC vs. DCS: Repeat A vs. Switch A | 0.64 | 0.41 | 1.56 | .12 |
| SLC vs. DCS: Repeat A vs. Switch A | 0.17 | 0.45 | 0.39 | .70 |
| DLC vs. DCS: Repeat M vs. Switch M | 0.08 | 0.53 | 0.15 | .88 |
| DLC vs. SLC: Repeat M vs. Switch M | -0.07 | 0.47 | -0.15 | .88 |
| SLC vs. DCS: Repeat M vs. Switch M | -0.15 | 0.49 | -0.30 | .76 |
| DLC vs. DCS: Switch A vs. Switch M | -0.11 | 0.41 | -0.26 | .80 |
| DLC vs. SLC: Switch A vs. Switch M | -0.05 | 0.37 | -0.14 | .89 |
| SLC vs. DCS: Switch A vs. Switch M | 0.06 | 0.39 | 0.14 | .87 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.64 | 0.80 |
| Condition | (Intercept) | 0.00 | 0.00 |

*Table 4.5.17: GLMM results of error analysis of local switch cost performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context; A: Alternate task condition; M: Mixed task condition).*

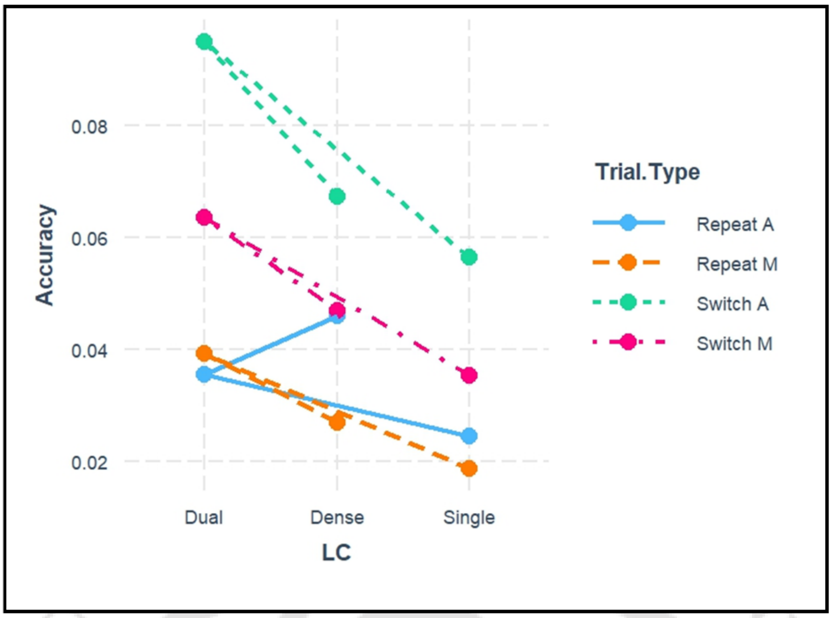


*Figure 4.5.11: Graph showing error analysis of local switch cost performance in univalent task. The lines connect the different LC groups across the different trial types, showing respective rates of accuracy. (A: Alternate task condition; M: Mixed task condition).*

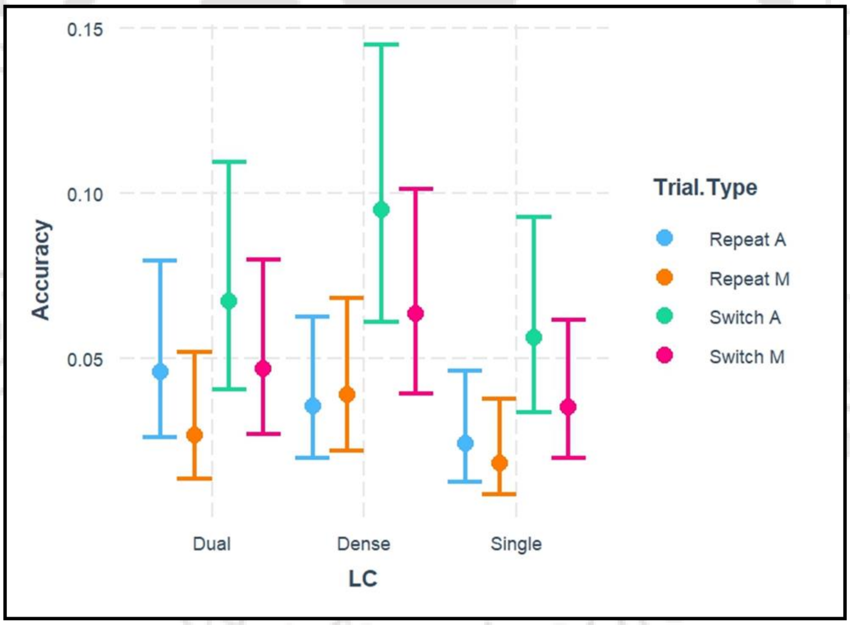


*Figure 4.5.12: Error analysis of each LC group of local switch cost performance in univalent task. Each coloured bar represents a different trial type. (A: Alternate task condition; M: Mixed task condition).*

Overall, while the intercept was significant, none of the main effects or interaction effects involving LC and trial type were statistically significant. This suggests that language context, trial type, and their interactions did not have a significant impact on accuracy in this model *(see figure 4.5.11, 4.5.12 for graphical representation)*.

### ***Post-error analysis***

A linear mixed-effects model was conducted to investigate the effects of post-error trials, Language Context (LC), and trial type on reaction times (RT) in a post-error analysis. The model included random intercepts for Subject and Condition, as well as random slopes for post-error trials across subjects. The random effects indicated substantial variability between participants (Variance = 14272, SD = 119.47) and conditions (Variance = 38662, SD = 196.63). Additionally, the random slope for Post Error across subjects had a variance of 4419 (SD = 66.47), with a negative correlation between the intercept and the post-error effect (Corr = -0.15). The weak negative correlation between the random intercept and slope within subjects suggests that participants' baseline response speeds are inverse, indicating that while slower responders tend to show smaller post-error effects, and faster responders tend to show larger effects.

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 834.8 | 198.7 | 0.000001 | 4.20 | 1.00 |
| Post error | 49.16 | 36.55 | 89.45 | 1.35 | .18 |
| ***LC*** | | | | | |
| DLC vs. DCS | 75.59 | 38.71 | 57.96 | 1.95 | *.05* |
| DLC vs. SLC | 56.25 | 38.69 | 57.87 | 1.45 | .15 |
| SLC vs. DCS | 19.34 | 37.74 | 58.04 | 0.51 | .61 |
| ***Trial type*** | | | | | |
| Repeat A vs Repeat M | -25.95 | 278.2 | 0.000001 | -0.09 | 1.00 |
| Repeat A vs. Switch A | 110.3 | 9.49 | 4525 | 11.62 | *< .001* |
| Repeat M vs. Switch M | 71.31 | 9.29 | 4524.52 | 7.68 | *< .001* |
| Switch A vs. Switch M | -64.90 | 340.52 | 4523.52 | -0.19 | .85 |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. DCS | 39.94 | 45.29 | 54.05 | 0.88 | .38 |
| Post error: DLC vs. SLC | 44.0 | 40.95 | 46.35 | 1.08 | .29 |
| Post error: SLC vs. DCS | 4.07 | 42.81 | 51.13 | 0.10 | .92 |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Repeat A vs Repeat M | 87.31 | 38.26 | 3546 | 2.28 | *.02* |
| Post error: Repeat A vs. Switch A | 18.53 | 37.95 | 2341 | 0.49 | .63 |
| Post error: Repeat M vs. Switch M | -120.32 | 43.00 | 2888.65 | -2.80 | *.005* |
| Post error: Switch A vs. Switch M | -51.53 | 42.08 | 3281.38 | -1.23 | .22 |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Corr** |
| Subject | (Intercept) | 14272 | 119.47 | |
| | Post Error | 4419 | 66.47 | -0.15 |
| Condition | (Intercept) | 38662 | 196.63 | |
| Residual | | 47812 | 218.66 | |

*Table 4.5.18: LMM results of post-error performance of local switch cost performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context; A: Alternate task condition; M: Mixed task condition).*

The effect of Post Error was not statistically significant, with an estimate of 49.16 (SE = 36.55, t = 1.35), with $p$ = .18, indicating that post-error trials did not significantly impact RT overall.

The interaction between Post-Error and LC was not significant for comparison of any of the levels. Analysis showed that Dual LC group had slower post-error performance than Single LC group and Dense CSC group. Single LC group had slower performance than Dense CSC group.

Interaction between post-error performance and trial types showed comparison between certain levels showed statistical significance. For example, when comparing performance between repeat trials of Alternate task condition and Mixed task conditions, there was an estimated difference of 87.31 *ms* (SE = 38.26, t = 2.28), with p = .02, where performance in Alternate condition were slower than Mixed condition. The repeat trials of Alternate task condition were slower than switch trials, but this difference was not significant. The switch trials of Mixed condition were slower than repeat trials of Mixed condition, with an estimated difference of 120.32 (SE = 43.0, t = -2.80), where p = .005, with performance in switch trials slower than repeat trials. The switch trials of Alternate task condition had slower post-error response however, this difference was not statistically significant.

### *Global Switch Cost*

Global Switch Cost is the difference in performance in the repeat trials of Mixed block and Pure block. The Alternate task block has also been included in this study.

### *RT analysis*

*Linear Mixed-Model Analysis*

A linear mixed-effects model (LMM) was conducted to examine the effects of LC, task condition, accuracy, and their interactions on response times (RTs). The model accounted for random intercepts for Subject, Display, and Task, indicating variability across these factors.

The random effects showed substantial variability across participants (Variance = 12,247, SD = 110.67), displays presented (Variance = 1332, SD = 36.49), and tasks performed (Variance = 1082, SD = 32.89). The residual variance was 39,814 (SD = 199.53), reflecting unexplained variability in RTs.

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 834.79 | 37.13 | 4.57 | 22.48 | *< .001* |
| ***LC*** | | | | | |
| DLC vs. DCS | 70.99 | 38.03 | 73.64 | 1.87 | *.07* |
| DLC vs. SLC | 58.47 | 37.99 | 73.36 | 1.54 | .13 |
| SLC vs. DCS | 12.52 | 37.10 | 73.89 | 0.34 | .74 |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Letter) | -29.76 | 16.02 | 4051.35 | -1.86 | *.06* |
| Alternate vs. Pure (Number) | -55.35 | 15.75 | 4277.39 | -3.51 | *.0004* |
| Alternate vs. Mixed | -6.02 | 15.11 | 4383.37 | -0.40 | .69 |
| Pure (Letter) vs. Pure (Number) | -25.59 | 17.74 | 2969.80 | -1.44 | .15 |
| Pure (Letter) vs. Mixed | 23.75 | 15.96 | 4154.84 | 1.49 | .14 |
| Pure (Number) vs. Mixed | 49.34 | 15.89 | 4236.22 | 3.11 | *.002* |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -24.40 | 26.85 | 4384.56 | -0.91 | .36 |
| ***LC x Condition interaction*** | | | | | |
| DLC vs. SLC: Alternate vs. Pure (Letter) | 39.32 | 20.74 | 4368.45 | 1.90 | *.06* |
| DLC vs. DCS: Alternate vs. Pure (Letter) | -13.87 | 20.77 | 4368.55 | -0.67 | .50 |
| SLC vs. DCS: Alternate vs. Pure (Letter) | -53.18 | 20.42 | 4368.81 | -2.60 | *.009* |
| DLC vs. SLC: Alternate vs. Pure (Number) | -46.04 | 20.73 | 4368.15 | -2.22 | *.03* |
| DLC vs. DCS: Alternate vs. Pure (Number) | -45.24 | 20.89 | 4368.25 | -2.17 | *.03* |
| SLC vs. DCS: Alternate vs. Pure (Number) | 0.80 | 20.44 | 4368.13 | 0.04 | .97 |
| DLC vs. SLC: Alternate vs. Mixed | -45.13 | 20.78 | 4368.24 | -2.17 | *.03* |
| DLC vs. DCS: Alternate vs. Mixed | -25.41 | 20.92 | 4368.02 | -1.22 | .22 |
| SLC vs. DCS: Alternate vs. Mixed | 19.72 | 20.56 | 4368.01 | 0.96 | .34 |
| DLC vs. SLC: Pure (Letter) vs. Pure (Number) | -85.36 | 20.83 | 4368.11 | -4.10 | *< .001* |
| DLC vs. DCS: Pure (Letter) vs. Pure (Number) | -31.38 | 20.91 | 4368.65 | -1.50 | .13 |
| SLC vs. DCS: Pure (Letter) vs. Pure (Number) | 53.98 | 20.46 | 4368.84 | 2.64 | *.008* |
| DLC vs. SLC: Pure (Letter) vs. Mixed | -84.44 | 20.87 | 4368.24 | -4.05 | *< .001* |
| DLC vs. DCS: Pure (Letter) vs. Mixed | -11.55 | 20.92 | 4368.45 | -0.55 | .58 |
| SLC vs. DCS: Pure (Letter) vs. Mixed | 72.90 | 20.60 | 4368.81 | 3.54 | *.0004* |
| DLC vs. SLC: Pure (Number) vs. Mixed | 0.91 | 20.87 | 4367.82 | 0.04 | .97 |
| DLC vs. DCS: Pure (Number) vs. Mixed | 19.83 | 21.06 | 4368.18 | 0.94 | .35 |
| SLC vs. DCS: Pure (Number) vs. Mixed | 18.92 | 20.62 | 4368.32 | 0.92 | .36 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | 47.90 | 39.69 | 4387.75 | 1.21 | .23 |
| DLC vs. DCS: Correct vs. Error | 28.27 | 35.96 | 4385.02 | 0.79 | .43 |
| SLC vs. DCS: Correct vs. Error | -19.62 | 37.83 | 4389.88 | -0.52 | .60 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 12247 | 110.67 |
| Display | (Intercept) | 1332 | 36.49 |
| Task | (Intercept) | 1082 | 32.89 |
| Residual | | 39814 | 199.53 |

*Table 4.5.19: LMM results of RT analysis of global switch cost performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

For the fixed effect of Language Context (LC), the comparison between DLC vs. DCS approached significance with an estimated difference of 70.99 *ms* (SE = 38.03, t = 1.87), with $p = .07$, where performance in DLC was faster than DCS. Performance in Dual LC was faster than Single LC group, but not significantly so. Similarly, Single LC group showed faster performance than Dense CSC group, however this difference was not statistically significant.

In terms of Task Condition, performance in Alternate condition showed significantly higher RTs compared to the Pure (Number) condition where there was an estimated difference of 55.35 *ms* (SE = 15.75, t = -3.51), with $p < .001$. Performance in Pure (Letter), and Mixed task conditions were faster than Alternate task condition. Mixed condition showed slower performance than Pure (Letter) and Pure (Number). Comparison between Mixed condition and Pure (Number) showed an estimated difference of 49.34 *ms* (SE = 15.89, t = 3.11), with $p = .002$. Pure (Number) showed faster performance than Pure (Letter).

The fixed effect of Accuracy was not significant, with Correct vs. Error trials showing a non-significant difference in RTs with an estimated difference of 24.40 *ms* (SE = 26.85, t = -0.91), with $p = .36$, where errors showed faster performance than correct responses. This would be further explored in the Error analysis section.

The interaction between LC and Task Condition revealed a significant effect for comparison among certain levels, for instance, for DLC vs. SLC in the Pure (Letter) vs. Pure (Number) comparison, with an estimated difference of 85.36 *ms* (SE = 20.83, t = -4.10), with $p < .001$, indicating that LC effects varied across these conditions. Additionally, comparing Dual LC group with Single LC group, for the Alternate vs. Pure (Number) condition showed a significant interaction with an estimated difference of 46.04 *ms* (SE = 20.73, t = -2.22), with $p = .03$. Similarly, when comparing Dual LC and Dense CSC groups for the same task conditions, the difference was also significant, displaying an estimated difference of 45.13 *ms* (SE = 20.78, t = -2.17), where $p = .03$. In contrast, when comparing most of the other levels in various task conditions, the estimated differences were not significant. This meant that while the performances of the LC groups in the different task conditions differed, their differences were not statistically significant.

In the interaction between LC and Accuracy, there was not significance found in either the Dual LC group vs. Single LC group comparison or in the Dual LC vs. Dense CS group comparison, indicating no significant modulation of LC effects by accuracy.

In summary, the model identified significant effects of task condition and some interactions between LC and task condition, while accuracy effects were generally non-significant.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 147629 | 73814 | 2 | 88.7 | 1.85 | .16 |
| ***Condition*** | 3097494 | 1032498 | 3 | 2672.9 | 25.93 | *< .001* |
| ***Accuracy*** | 160 | 160 | 1 | 4396.9 | 0.004 | .95 |
| ***LC: Condition*** | 1119788 | 186631 | 6 | 4368.3 | 4.69 | *< .001* |
| ***LC: Accuracy*** | 59690 | 29845 | 2 | 4387.5 | 0.75 | .43 |

*Table 4.5.20: Type III Analysis of Variance Table with Satterthwaite's method of global switch cost performance in univalent task.*

A Type III ANOVA was conducted to assess the effects of language context (LC), task condition, accuracy, and their interactions on the dependent variable, RT.

The main effect of LC was not statistically significant, F(2, 88.7) = 1.85, $p$ = .16, suggesting that the differences between the different language context groups did not significantly influenced the RT. The main effect of task condition was significant, F(3, 2672.9) = 25.93, with $p$ < .001, indicating substantial differences in the RT across various task conditions. The effect of accuracy was not significant, F(1, 4396.9) = 0.004, with $p$ = .95, suggesting that the accuracy of responses did not significantly affect the outcome.

The interaction between LC and task condition was significant, F(6, 4368.3) = 4.69, with $p$ < .001, indicating that the effect of language context varied depending on the task condition. However, the interaction between LC and accuracy was not significant, F(2, 4387.5) = 0.75, where $p$ = .43, suggesting that the influence of LC did not differ based on accuracy.

In summary, the analysis revealed a significant main effect of condition and a significant LC by condition interaction, while no significant effects were found for LC or accuracy, nor for their interaction.

## ***Post-HOC analysis***

*EM Means- Language context*

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 869 | 37.6 | 4.82 | 772 | 967 |
| ***Dual*** | 800 | 37.9 | 5.00 | 702 | 897 |
| ***Dense*** | 864 | 36.6 | 4.82 | 765 | 962 |

*Table 4.5.21: Group-wise EM Means based on Language Context of global switch cost performance in univalent task.*

A post-HOC analysis *(table 4.5.21)* of EM means for language context (LC) revealed that the Dual LC group had the lowest estimated mean of 800 *ms* (SE = 37.9, df = 5.0, 95% CI [702, 897]). Dense CSC group had an estimated mean of 864 *ms* (SE = 36.6, df = 4.82, 95% CI [765, 962]). Single LC group had an estimated mean of 869 *ms* (SE = 37.6, df = 4.82, 95% CI [772, 967]). Thus, Dual LC group had the fastest average performance, followed by Dense CSC group, and finally the Single LC group, although the mean difference between Single LC group and Dense CSC group was minimal *(see figure 4.5.13 for graphical representation)*.

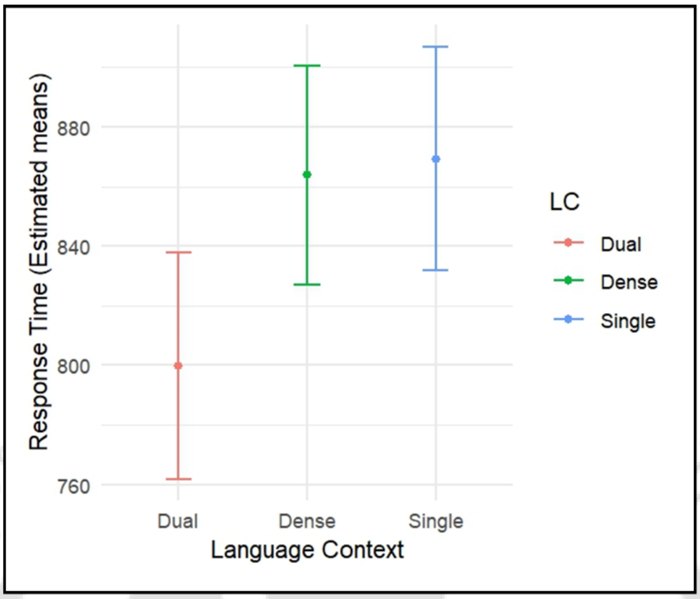


*Figure 4.5.13: Group-wise EM Means performance based on Language Context of global switch cost performance in univalent task. Dual LC group shows the least EM means, followed by Dense CSC group, which was closely followed by Single LC group. Bars represent 95% confidence intervals.*

*Pairwise analysis- Language context*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -64.0 | 39.4 | 84.5 | -1.63 | .24 |
| ***Dual - Single*** | -69.46 | 40.2 | 92.2 | -1.73 | .20 |
| ***Dense - Single*** | -5.46 | 39.0 | 90.2 | -0.14 | .99 |

*Table 4.5.22: Pair-wise analysis based on Language context of global switch cost performance in univalent task.*

A pairwise comparison of the LC group levels showed that none of the pairwise differences showed statistical significance. The difference between Dual LC group and Dense CSC group had an estimated difference of 64.0 *ms* (SE = 39.4, df = 84.5, t = −1.63), with *p* = .24, where Dual LC had faster performance than Dense CSC group. Similarly, the comparison between the Dual LC and Single LC groups revealed a non-significant difference of 69.46 *ms* (SE = 40.2, df = 92.2, t = −1.73), with *p* = .20, where Dual LC were faster than Single LC group. Lastly, the difference between the Dense CSC and Single LC groups was minimal and also non-significant, with an estimated difference of 5.46 *ms* (SE = 39.0, df = 90.2, t = -0.14), *p* = .99, with Dense CSC group shown to be faster than Single LC group. None of the contrasts reached conventional levels of statistical significance.

*EM Means- Task condition*

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Pure (Number)*** | 793 | 30.5 | 2.09 | 667 | 918 |
| ***Pure (Letter)*** | 857 | 30.4 | 2.09 | 731 | 983 |
| ***Alternate*** | 878 | 30.1 | 2.02 | 750 | 1007 |
| ***Mixed*** | 849 | 30.2 | 2.04 | 721 | 977 |

*Table 4.5.23: Group-wise EM Means based on task condition of global switch cost performance in univalent task.*

The estimated marginal means (EM means) for the task condition variable revealed *(table 4.5.23)* that the Pure (Number) condition had the least EM mean of 793 *ms* (SE = 30.5, df = 2.09, 95% CI [667, 918]). Next, Mixed condition had an EM mean of 849 *ms* (SE = 30.2, df = 2.04, 95% CI [721, 977]). Pure (Letter)condition had higher EM mean of 857 *ms* (SE = 30.4, df = 2.09, 95% CI [731, 983]). Finally, Alternate condition showed the highest EM mean at 878 *ms* (SE = 30.1, df = 2.02, 95% CI [750, 1007]). These means indicate some variability across conditions, with the Alternate condition having the highest mean performance, and Pure (Number) showed the lowest mean performance *(see figure 4.5.14 for graphical representation)*.

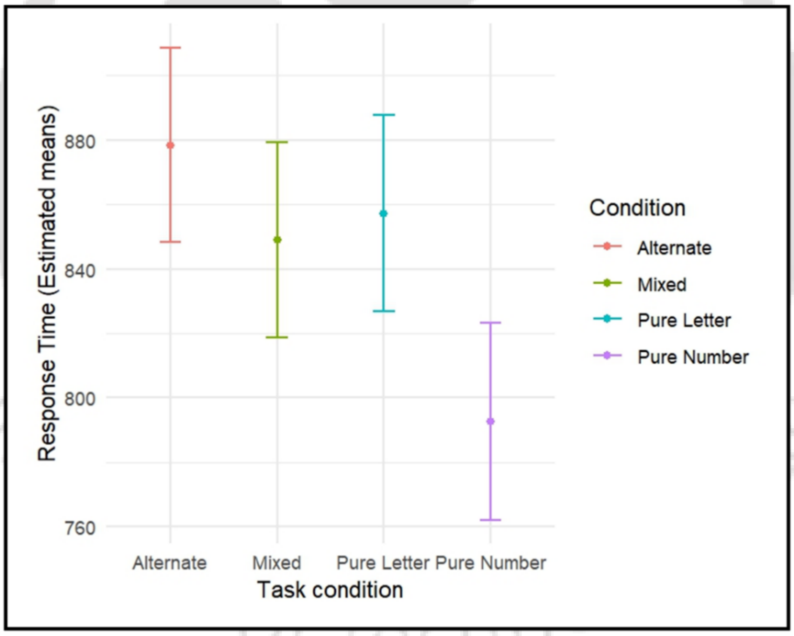


*Figure 4.5.14: Group-wise EM Means performance based on task condition of global switch cost performance in univalent task. Performance in Pure (Number) task condition was the fastest, followed by Mixed condition, closely followed by Pure (Letter), and finally Alternate task condition. Bars represent 95% confidence intervals.*

*Pairwise analysis- Task condition*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Pure (Letter) - Pure (Number)*** | 64.50 | 13.2 | 1502 | 4.88 | *< .0001* |
| ***Alternate - Pure (Number)*** | 85.78 | 9.9 | 3637 | 8.66 | *< .0001* |
| ***Alternate - Pure (Letter)*** | 21.28 | 10.5 | 2754 | 2.02 | .18 |
| ***Alternate - Mixed*** | 29.53 | 8.8 | 4334 | 3.36 | *.004* |
| ***Mixed - Pure (Number)*** | 56.25 | 10.1 | 3383 | 5.58 | *< .0001* |
| ***Mixed - Pure (Letter)*** | -8.25 | 10.3 | 3105 | -0.80 | .85 |

*Table 4.5.24: Pair-wise analysis based on task condition of global switch cost performance in univalent task.*

The pairwise comparison analysis revealed significant differences between task conditions *(table 4.5.24)*. Most of the pairwise comparisons showed statistical significance. Pure (Letter) condition had a significantly higher estimated marginal mean compared to Pure (Number) condition, with an estimate of 64.50 *ms* (SE = 13.2, df = 1502, t = 4.88) with $p < .0001$. Alternate task condition demonstrated a significantly higher RT than Pure (Number) task condition, with an estimate of 85.78 *ms* (SE = 9.9, df = 3637, t = 8.66), with $p < .0001$. Alternate condition also had significantly higher mean RT than Mixed task condition, with an estimate of 29.53 *ms* (SE = 8.8, df = 4334, t = 3.36), with $p = .004$. Performance in Mixed condition was slower than Pure (Number) condition, with an estimate of 56.25 *ms* (SE = 10.1, df = 3383, t = 5.58), with $p < .0001$.

Some of the pairwise comparisons did not achieve statistical significance, showing that although there were differences between the task conditions in performance, this difference was not significant. Mixed condition showed faster performance than Pure (Letter) task condition, with an estimated difference of 8.25 *ms* (SE = 10.3, df = 3105, t = 0.80), with $p = .85$, however this difference was not significant. Comparing Alternate and Pure (Letter) conditions, Alternate condition showed higher mean RT, with an estimate of 21.28 *ms* (SE = 10.5, df = 2754, t = 2.02), with $p = .18$, this difference was also not significant.

*EM Means- LC * Condition*

| LC | Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Pure (Number)*** | 804 | 38.8 | 5.47 | 706 | 901 |
| ***Single*** | ***Pure (Letter)*** | 915 | 38.9 | 5.47 | 817 | 1012 |
| ***Single*** | ***Alternate*** | 905 | 38.7 | 5.40 | 808 | 1002 |
| ***Single*** | ***Mixed*** | 854 | 38.8 | 5.49 | 757 | 951 |
| ***Dual*** | ***Pure (Number)*** | 767 | 39.4 | 5.74 | 670 | 865 |
| ***Dual*** | ***Pure (Letter)*** | 793 | 39.4 | 5.78 | 695 | 890 |
| ***Dual*** | ***Alternate*** | 823 | 39.0 | 5.55 | 725 | 920 |
| ***Dual*** | ***Mixed*** | 817 | 39.2 | 5.68 | 719 | 914 |
| ***Dense*** | ***Pure (Number)*** | 807 | 38.0 | 5.01 | 709 | 905 |
| ***Dense*** | ***Pure (Letter)*** | 864 | 38.0 | 5.0 | 766 | 962 |
| ***Dense*** | ***Alternate*** | 908 | 37.8 | 4.94 | 810 | 1005 |
| ***Dense*** | ***Mixed*** | 876 | 37.8 | 4.96 | 779 | 974 |

*Table 4.5.25: Group-wise EM Means based on interaction between LC and task condition of global switch cost performance in univalent task.*

The estimated marginal means (EMMs) for Language Context groups (LC) across difference task conditions show variations depending on the task condition *(table 4.5.25)*.

In Pure (Number) task condition, Dual LC group showed the fastest performance, with an estimated mean of 767 *ms* (SE = 39.4, df = 5.74, 95% CI [670, 865]). This was followed by Single LC group, with an estimated marginal mean of 804 *ms* (SE = 38.8, df = 5.47, 95% CI [706, 901]). Finally, the Dense CSC group, with a mean of 807 *ms* (SE = 38.0, df = 5.01, 95% CI [709, 905]).

In Pure (Letter) task condition, Dual LC group outperformed the other groups with an estimated mean of 793 *ms* (SE = 39.4, df = 5.78, 95% CI [695, 890]). Next came Dense CSC group which had an estimated mean of 864 *ms* (SE = 38.0, df = 5.0, 95% CI [766, 962]). Single LC group yielded the highest mean, with an estimate of 915 *ms* (SE = 38.9, df = 5.47, 95% CI [817, 1012]).

Alternate task condition also saw Dual LC group having fastest performance, with an estimated mean of 823 *ms* (SE = 39.0, df = 5.55, 95% CI [725, 920]). Single LC group had an estimated mean of 905 *ms* (SE = 38.7, df = 5.40, 95% CI [808, 1002]). Lastly, Dense CSC group had a mean of 908 *ms* (SE = 37.8, df = 4.94, 95% CI [810, 1005]).

Mixed task condition similarly, saw fastest performance by Dual LC group, resulting in a mean of 817 *ms* (SE = 39.2, df = 5.68, 95% CI [719, 914]). Single LC group followed, with a mean of 854 *ms* (SE = 38.8, df = 5.49, 95% CI [757, 951]). Finally came Dense CSC group 876 *ms* (SE = 37.8, df = 4.96, 95% CI [779, 974]).

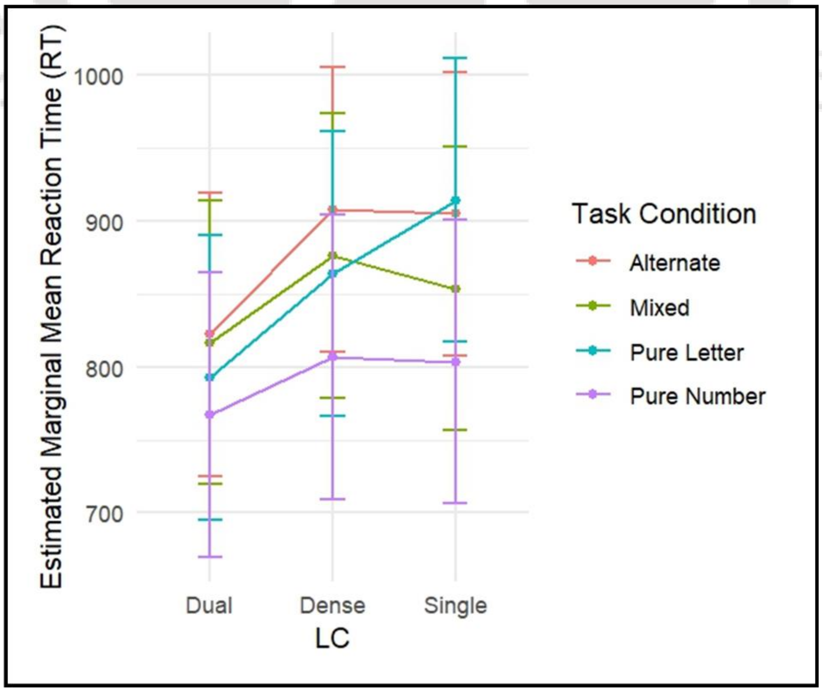


*Figure 4.5.15: Interaction of LC × Task condition of global switch cost performance in univalent task.*

These results indicate that the three LC groups generally had highest EM means while performing in Alternate task condition, and lowest EM means in Pure (Number) task condition. Dual LC group consistently outperformed the Single and Dense CSC groups in each task condition *(see figure 4.5.15 for graphical representation)*.

***Accuracy analysis***

*Error rate.* Error-rate analysis revealed that Single LC group had the least errors (3.33%), followed by Dual LC group (4.22%), and then came Dense CSC group (5.13%).

*GLMM.* A generalized linear mixed model (GLMM) was conducted to examine the effects of language context (LC), task condition, response time, and their interactions on accuracy in the participants' performances. Random intercepts were specified for participant and Task Type. The variance of the random effects for Subject was 0.65 (SD = 0.81), while the variance for Task Type was 0.07 (SD = 0.26). These random effects indicate some variability across subjects and task types, but the variability was relatively small.

For fixed effect of LC, comparisons between Dual LC group and Single LC group showed a significant effect, with an estimate of 0.78 (SE = 0.45, z = -1.73), with $p$ = .08, where the accuracy in Dual LC group was shown to be marginally significantly lower than Single LC group. However, the other comparisons were not significant and it was found that Dense CSC group had lesser errors than Dual LC group, and Single LC group had lesser errors than Dense CSC group.

In terms of task condition, none of the task condition comparisons showed statistical significance, thus implying that difference in task conditions had no significant impact on the accuracy related performance. Comparisons showed that lesser errors occurred in Pure (Number), Pure (Letter), and Mixed task conditions as compared to Alternate task condition. Mixed task condition had lesser errors than Pure (Letter) and Pure (Number) conditions. Between Pure (Letter) and Pure (Number), Pure (Letter) had lesser errors.

Similarly, for RT (scaled), no significant effect was found, with an estimate of 0.016 (SE = 0.06, z = 0.27), and $p$ = .79, indicating that response time did not have a substantial impact on the accuracy of the performance. In the interaction effects, significant interactions were found for certain LC groups only in their performance comparison between Alternate and Pure (Letter) task conditions. When comparing Dual LC group with Single LC group, in this task comparison, there was an estimate difference of 1.06 (SE = 0.54, z = 1.97), with $p$ = .05. The difference between Dual LC group and Dense CSC group was only marginally significant, with an estimate of 0.90 (SE = 0.51, z = 1.76), with $p$ = .08. Thus, these results suggest that language context groups interacting with task conditions had no influence on the outcome, except in comparing performances in Alternate and Pure (Letter) tasks.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -3.04 | 0.35 | -8.72 | < *.001* |
| ***LC*** | | | | |
| DLC vs. SLC | -0.78 | 0.45 | -1.73 | *.08* |
| DLC vs. DCS | -0.37 | 0.43 | -0.88 | .38 |
| SLC vs. DCS | 0.41 | 0.46 | 0.89 | .38 |
| ***Task condition*** | | | | |
| Alternate vs. Pure (Letter) | -0.50 | 0.41 | -1.22 | .22 |
| Alternate vs. Pure (Number) | -0.39 | 0.34 | -1.13 | .26 |
| Alternate vs. Mixed | -0.59 | 0.36 | -1.64 | .10 |
| Pure (Letter) vs. Pure (Number) | 0.11 | 0.47 | 0.23 | .82 |
| Pure (Letter) vs. Mixed | -0.09 | 0.45 | -0.21 | .84 |
| Pure (Number) vs. Mixed | -0.20 | 0.39 | -0.52 | .60 |
| ***Response time*** | | | | |
| RT (scaled) | 0.10 | 0.08 | 1.35 | .18 |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Alternate vs. Pure (Letter) | 1.06 | 0.54 | 1.97 | *.05* |
| DLC vs. DCS: Alternate vs. Pure (Letter) | 0.90 | 0.51 | 1.76 | *.08* |
| SLC vs. DCS: Alternate vs. Pure (Letter) | -0.17 | 0.51 | -0.33 | .74 |
| DLC vs. SLC: Alternate vs. Pure (Number) | 0.40 | 0.51 | 0.78 | .43 |
| DLC vs. DCS: Alternate vs. Pure (Number) | 0.56 | 0.46 | 1.21 | .23 |
| SLC vs. DCS: Alternate vs. Pure (Number) | 0.16 | 0.50 | 0.32 | .75 |
| DLC vs. SLC: Alternate vs. Mixed | 0.18 | 0.58 | 0.31 | .76 |
| DLC vs. DCS: Alternate vs. Mixed | 0.69 | 0.50 | 1.39 | .16 |
| SLC vs. DCS: Alternate vs. Mixed | 0.51 | 0.57 | 0.91 | .36 |
| DLC vs. SLC: Pure (Letter) vs. Pure (Number) | -0.67 | 0.52 | -1.25 | .21 |
| DLC vs. DCS: Pure (Letter) vs. Pure (Number) | -0.34 | 0.51 | -0.67 | .51 |
| SLC vs. DCS: Pure (Letter) vs. Pure (Number) | 0.33 | 0.48 | 0.69 | .49 |
| DLC vs. SLC: Pure (Letter) vs. Mixed | -0.88 | 0.60 | -1.47 | .14 |
| DLC vs. DCS: Pure (Letter) vs. Mixed | -0.20 | 0.54 | -0.38 | .71 |
| SLC vs. DCS: Pure (Letter) vs. Mixed | 0.68 | 0.54 | 1.25 | .21 |
| DLC vs. SLC: Pure (Number) vs. Mixed | 0.13 | 0.49 | 0.27 | .79 |
| DLC vs. DCS: Pure (Number) vs. Mixed | -0.22 | 0.57 | -0.38 | .71 |
| SLC vs. DCS: Pure (Number) vs. Mixed | 0.35 | 0.54 | 0.65 | .52 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.65 | 0.81 |
| Task | (Intercept) | 0.07 | 0.26 |

*Table 4.5.26: GLMM results of error analysis of global switch cost performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

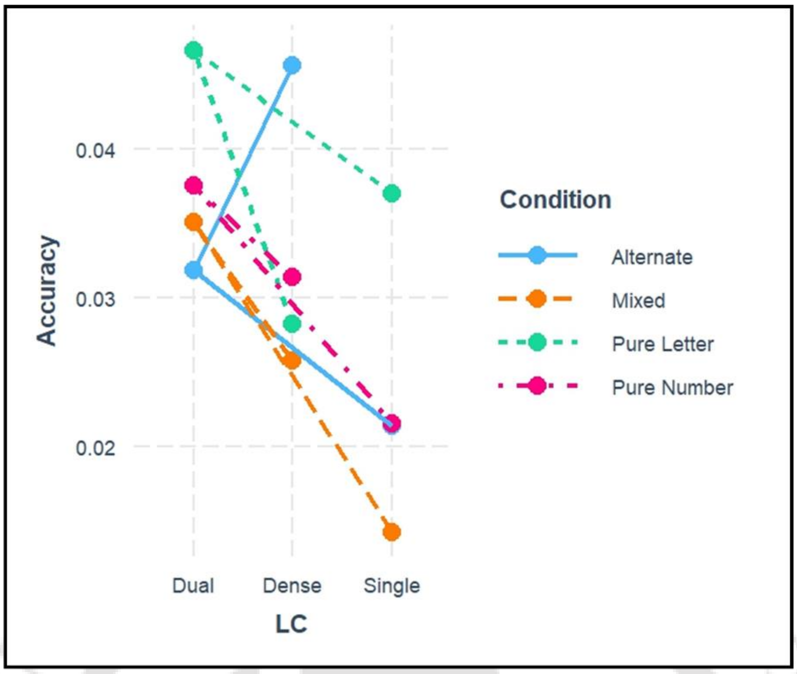


*Figure 4.5.16: Graph showing error analysis of overall performance in global switch cost performance in univalent task. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

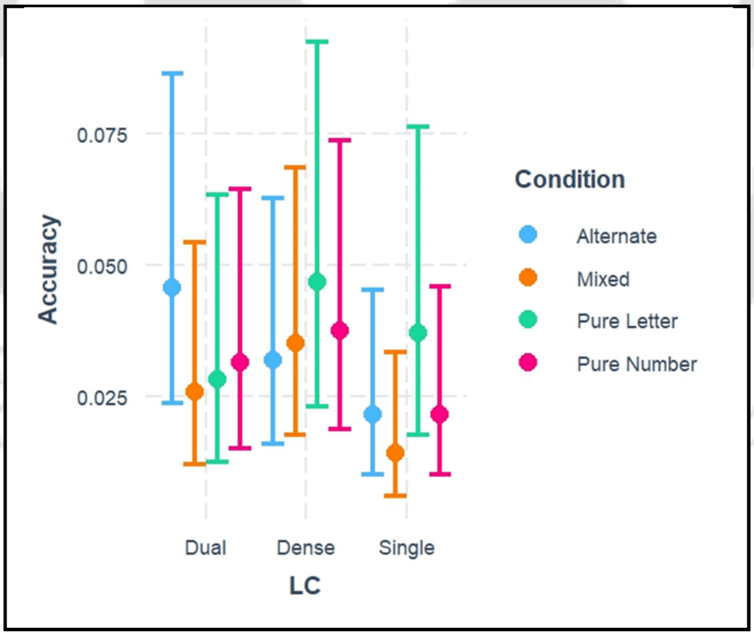


*Figure 4.5.17: Error analysis of each LC group in overall performance in global switch cost performance in univalent task. Each coloured bar represents a different task condition.*

Overall, the analysis highlights a significant difference between the Alternate and Mixed conditions, a marginally significant difference between Dual LC group and Single LC group, and interaction effect in one condition, but no strong effects of response time, nor most of the interactions between LC and task condition *(see figure 4.5.16, 4.5.17 for graphical representation)*.

### *Post-error analysis*

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 837.88 | 37.16 | 3.78 | 22.55 | < *.001* |
| Post error | -1.25 | 36.18 | 38.85 | -0.04 | .97 |
| ***LC*** | | | | | |
| DLC vs. SLC | 47.20 | 35.64 | 57.82 | 1.33 | .19 |
| DLC vs. DCS | 49.54 | 35.65 | 57.92 | 1.39 | .17 |
| SLC vs. DCS | 2.33 | 34.76 | 57.98 | 0.07 | .95 |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Letter) | -18.22 | 9.73 | 3908.48 | -1.87 | *.06* |
| Alternate vs. Pure (Number) | -89.03 | 9.71 | 3950.70 | -9.17 | < *.001* |
| Alternate vs. Mixed | -24.89 | 8.76 | 4326.69 | -2.84 | *.005* |
| Pure (Letter) vs. Pure (Number) | -70.79 | 12.22 | 2554.58 | -5.80 | < *.001* |
| Pure (Letter) vs. Mixed | -6.67 | 9.79 | 3995.13 | -0.68 | .50 |
| Pure (Number) vs. Mixed | 64.12 | 9.75 | 4060.02 | 6.58 | < *.001* |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | 9.62 | 37.16 | 15.00 | 0.26 | .80 |
| Post error: DLC vs. DCS | 9.69 | 40.90 | 17.28 | 0.24 | .82 |
| Post error: SLC vs. DCS | -0.07 | 38.79 | 13.98 | -0.002 | .99 |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Alternate vs. Pure (Letter) | 37.87 | 43.34 | 689.90 | 0.87 | .38 |
| Post error: Alternate vs. Pure (Number) | 159.99 | 41.64 | 424.39 | 3.84 | *.0001* |
| Post error: Alternate vs. Mixed | 95.03 | 44.56 | 762.93 | 2.13 | *.03* |
| Post error: Pure (Letter) vs. Pure (Number) | 122.21 | 42.37 | 2188.08 | 2.88 | *.004* |
| Post error: Pure (Letter) vs. Mixed | 57.25 | 45.21 | 2704.79 | 1.27 | .21 |
| Post error: Pure (Number) vs. Mixed | -64.97 | 43.63 | 2706.05 | -1.49 | .14 |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Corr.** |
| Subject | (Intercept) | 12088.2 | 109.95 | |
| | Post Error | 214.2 | 14.64 | 0.68 |
| Task | (Intercept) | 1372.1 | 37.04 | |
| Residual | | 40951.5 | 202.36 | |

*Table 4.5.27: LMM results of post-error performance of global switch cost performance in univalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed-effects model was conducted to examine the effects of post-error adjustments, language context, and task condition on response times (RT). The random intercept for Subject had a variance of 12,088.2 (SD = 109.95), reflecting notable individual differences in baseline RTs. Additionally, the random slope for Post-error within subjects showed variability, with a variance of 214.2 (SD = 14.64), indicating differences in how individuals adjust their RTs following an error. The correlation between the random intercept and the random slope for Post-error was moderately positive (r = 0.68), suggesting that individuals with higher baseline RTs also tended to exhibit larger post-error effects.

The variability across tasks was smaller, with a variance of 1,372.1 (SD = 37.04). This result indicates relatively consistent performance across tasks compared to the variability observed at the subject level. The residual variance was 40,951.5 (SD = 202.36), indicating a substantial amount of unexplained variability in RTs.

There was no significant main effect of Post-error, suggesting that post-error slowing did not reliably occur across trials.

In terms of interaction effects, there was no significant effect between post-error and LC grouping. Analysis showed Dual LC group slower post-error performance than Single LC group and Dense CSC group. Dense CSC group showed slower performance than Single LC group.

There were significant interactions between post-error and performance comparison between some levels of task condition performance. For example, Alternate task condition showed slower performance than Pure (Letter), Pure (Number) and Mixed task conditions. Alternate and Pure (Number) conditions had significant effect, with an estimate of 159.99 *ms* (SE = 41.64, t = 3.84), where $p < .001$. Similarly, comparing Alternate and Mixed task conditions also showed statistical significance, with an estimate of 95.03 *ms* (SE = 44.56, t = 2.13), where $p = .03$. Comparing post-error performances between Pure (Letter) and Pure (Number) showed slower post-error performance in Pure (Letter) condition, with an estimated difference of 122.21 *ms* (SE = 42.37, t = 2.88), with $p = .03$. Pure (Letter) also showed slower performance compared to Mixed condition, but this difference was not statistically significant. Mixed condition had slower post-error performance than Pure (Number), and this difference was similarly not significant.

These results suggest that post-error adjustments primarily affect specific task conditions, while language context does not appear to modulate significant post-error slowing.

#### 4.5.4.2 Bivalent Task

Analysis for bivalent task was done similarly as for univalent task. The participants were analysed for their overall performance in the task, local switch cost and global switch cost. In each of these, analysis was done on speed as well as accuracy.

***RT analysis***

*Linear Mixed-Model Analysis*

A linear mixed model was conducted to assess the effects of language context (LC), task condition, and accuracy on response times, as well as their interactions.

The model included random intercepts for participants, display, task, and trial type. The analysis revealed significant random intercept variances for participants with a variance of 16041.3 (SD =

126.7), display having a variance of 424.4 (SD = 20.6), and task with a variance of 479.7 (SD = 21.9), while the variance for trial type was zero. The residual variance was 71439.5 (SD = 267.3).

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 683.52 | 35.90 | 19.77 | 19.04 | < *.001* |
| ***LC*** | | | | | |
| DLC vs. SLC | 3.08 | 42.41 | 67.14 | 0.07 | .94 |
| DLC vs. DCS | 128.81 | 42.44 | 67.29 | 3.04 | *.003* |
| SLC vs. DCS | 125.73 | 41.40 | 67.52 | 3.04 | *.003* |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Colour) | -62.59 | 17.77 | 6449.61 | -3.52 | *.0004* |
| Alternate vs. Pure (Shape) | -112.84 | 17.44 | 6447.73 | -6.47 | < *.001* |
| Alternate vs. Mixed | -10.03 | 13.92 | 6854.62 | -0.72 | .47 |
| Pure (Colour) vs. Pure (Shape) | -50.25 | 21.29 | 4558.97 | -2.36 | *.02* |
| Pure (Colour) vs. Mixed | 52.56 | 17.68 | 6462.77 | 2.97 | *.003* |
| Pure (Shape) vs. Mixed | 102.81 | 17.87 | 6416.55 | 5.92 | < *.001* |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -56.53 | 32.56 | 6864.00 | -1.74 | *.08* |
| ***LC x Condition interaction*** | | | | | |
| DLC vs. SLC: Alternate vs. Pure (Colour) | -10.30 | 23.94 | 6854.23 | -0.43 | .67 |
| DLC vs. DCS: Alternate vs. Pure (Colour) | -7.46 | 24.10 | 6854.41 | -0.31 | .76 |
| SLC vs. DCS: Alternate vs. Pure (Colour) | 2.85 | 23.51 | 6854.35 | 0.12 | .90 |
| DLC vs. SLC: Alternate vs. Pure (Shape) | 52.92 | 23.75 | 6854.54 | 2.23 | *.03* |
| DLC vs. DCS: Alternate vs. Pure (Shape) | 97.11 | 23.64 | 6854.46 | 4.11 | < *.001* |
| SLC vs. DCS: Alternate vs. Pure (Shape) | -44.19 | 23.33 | 6854.63 | -1.90 | *.06* |
| DLC vs. SLC: Alternate vs. Mixed | 16.83 | 19.31 | 6854.32 | 0.87 | .38 |
| DLC vs. DCS: Alternate vs. Mixed | 0.82 | 19.43 | 6854.34 | 0.04 | .97 |
| SLC vs. DCS: Alternate vs. Mixed | -16.01 | 19.04 | 6854.46 | -0.84 | .40 |
| DLC vs. SLC: Pure (Colour) vs. Pure (Shape) | 107.42 | 27.49 | 6854.15 | 3.91 | < *.001* |
| DLC vs. DCS: Pure (Colour) vs. Pure (Shape) | 60.38 | 27.63 | 6854.09 | 2.19 | *.03* |
| SLC vs. DCS: Pure (Colour) vs. Pure (Shape) | -47.04 | 27.06 | 6854.28 | -1.74 | *.08* |
| DLC vs. SLC: Pure (Colour) vs. Mixed | 27.14 | 23.86 | 6854.11 | 1.14 | .26 |
| DLC vs. DCS: Pure (Colour) vs. Mixed | 8.28 | 24.02 | 6854.14 | 0.35 | .73 |
| SLC vs. DCS: Pure (Colour) vs. Mixed | -18.86 | 23.46 | 6854.22 | -0.80 | .42 |
| DLC vs. SLC: Pure (Shape) vs. Mixed | -80.28 | 23.56 | 6854.39 | -3.41 | *.0007* |
| DLC vs. DCS: Pure (Shape) vs. Mixed | -52.10 | 23.64 | 6854.14 | -2.20 | *.03* |
| SLC vs. DCS: Pure (Shape) vs. Mixed | 28.18 | 23.26 | 6854.49 | 1.21 | .23 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | 1.67 | 40.48 | 6880.78 | 0.04 | .97 |
| DLC vs. DCS: Correct vs. Error | -53.41 | 41.15 | 6867.87 | -1.30 | .19 |
| SLC vs. DCS: Correct vs. Error | 55.09 | 34.86 | 6891.94 | 1.58 | .11 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 16041.3 | 126.7 |
| Display | (Intercept) | 424.4 | 20.6 |
| Task | (Intercept) | 479.7 | 21.9 |
| Trial Type | (Intercept) | 0.0 | 0.0 |
| Residual | | 71439.5 | 267.3 |

*Table 4.5.28: LMM results of RT analysis of overall performance in bivalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

In terms of fixed effects, the intercept was significant with an estimate of 683.52 *ms* (SE = 35.90, t = 19.04), with $p$ <.001, indicating a strong overall effect. For the fixed effect of language context, a significant difference was found between Dual LC and Dense CSC groups, with an estimated difference of 128.82 *ms* (SE = 42.44, t = 3.04), with $p$ = .003, where performance of Dual LC group was faster than Dense CSC group. The difference between Single LC group and Dense CSC group was significantly significant, with an estimated difference of 125.73 *ms* (SE = 41.40, t = 3.04), with p = .003, where performance in Single LC group was faster than Dense CSC group. Dual LC group had faster performance than Single LC group, this difference was not significant.

Task condition also significantly impacted the performance of the participants. Performance difference of Alternate and Pure (Colour) task conditions showed significance, with an estimate of 62.59 *ms* (SE = 17.77, t = −3.52), with $p$ = .0004, where performance in Pure (Colour) task condition was faster than in Alternate task condition. Similarly, when comparing Alternate and Pure (Shape) conditions, there was a significant difference, with an estimate of 112.84 *ms* (SE = 17.44, t = −6.47), with $p$ <.001, with performance of Pure (Shape) condition faster than Alternate condition. However, when comparing performance in Alternate and Mixed conditions, the difference was not significant, with an estimate of 10.03 *ms* (SE = 13.92, t = −0.72) and $p$ = .47.

Although there was a trend toward significance for Accuracy, when comparing performance of correct and wrong response, the estimated difference was 56.53 *ms* (SE = 32.56, t = −1.74), where the error responses were shown to be faster. This difference, however, was marginally significant, with $p$ = .08.

The interaction between LC and task condition showed a significant effect of task condition on LC grouping for several levels. For instance, for Dual LC versus Single LC groups in the Alternate versus Pure (Shape) conditions, had an estimated difference of 52.92 *ms* (SE = 23.75, t = 2.23), where $p$ = .03. For the contrast of Dual LC group with Dense CSC group in the Alternate versus Pure (Shape) conditions, there was an estimated difference of 97.11 *ms* (SE = 23.64, t = 4.11), with $p$ < .001. However, no significant effects were found for the remaining LC x condition interactions. Lastly, no significant interaction was found between LC and task accuracy, with all comparisons yielding non-significant results.

Overall, the analysis demonstrates significant effects of linguistic context and task condition on response times, with notable interactions between linguistic context and task conditions for shape-related tasks.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 989981 | 494990 | 2 | 82.2 | 6.92 | *.002* |
| ***Condition*** | 6210970 | 2070323 | 3 | 3389.5 | 28.98 | *< .001* |
| ***Accuracy*** | 1533028 | 1533028 | 1 | 6882.4 | 21.46 | *< .001* |
| ***LC: Condition*** | 149870 | 249778 | 6 | 6854.3 | 3.50 | *.002* |
| ***LC: Accuracy*** | 210246 | 105123 | 2 | 6881.1 | 1.47 | .23 |

*Table 4.5.29: Type III Analysis of Variance Table with Satterthwaite's method of overall performance in bivalent task.*

A type III analysis of variance (ANOVA) was conducted to examine the effects of language context (LC), task condition, and accuracy, as well as their interactions, on response times. The results revealed a significant main effect of LC, $F(2, 82.2) = 6.92$, $p = .002$, indicating that the different LC groups had significantly different RTs from one another. Similarly, Task condition also had a significant main effect, $F(3, 3389.5) = 28.98$, $p < .001$, suggesting that the different task conditions also had a substantial impact on reaction times of the participants.

Accuracy significantly affected response times as well, $F(1, 6882.4) = 21.46$, $p < .001$, showing that the difference in performance between correct and wrong responses were significant. The interaction between LC and task condition was also significant, $F(6, 6854.3) = 3.50$, $p = .002$, indicating that the effect of task condition on response times varied depending on the LC grouping.

However, the interaction between linguistic context and accuracy was not significant, $F(2, 6881.1) = 1.47$, $p = .23$, suggesting that the relationship between accuracy and response times was not influenced by LC.

These findings suggest that both, LC and task condition, significantly influence participants' response times, and that their interaction further modulates this effect. Accuracy also plays a critical role, though its interaction with linguistic context does not appear to be significant.

## ***Post-HOC analysis***

*EM Means- Language context*

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 611 | 35.9 | 19.9 | 536 | 686 |
| ***Dual*** | 609 | 38.5 | 25.4 | 530 | 688 |
| ***Dense*** | 750 | 35.7 | 19.4 | 676 | 825 |

*Table 4.5.30: Group-wise EM Means based on Language Context of overall performance in bivalent task.*

An estimated marginal means (EMM) analysis was conducted to explore the performance of various language context groups in the overall performance of the bivalent task *(table 4.5.30)*. The results indicated that response times were fastest in Dual LC group, with an estimated mean RT of 609 *ms* (SE = 38.5, df = 25.4, 95% CI [530, 688]). They were closely followed by Single LC group, with an estimated mean of 611 *ms* (SE = 35.9, df = 19.9, 95% CI [536, 686]). However, Dense CSC group had the slowest performance, with an estimate of 750 *ms* (SE = 35.7, df = 19.4, 95% CI [676, 825]).

Thus, these results suggest that Dual LC group had the fastest performance, followed by Single LC group, although the difference between then was marginal, and finally came Dense CSC group at the end *(see figure 4.5.18 for graphical representation)*.

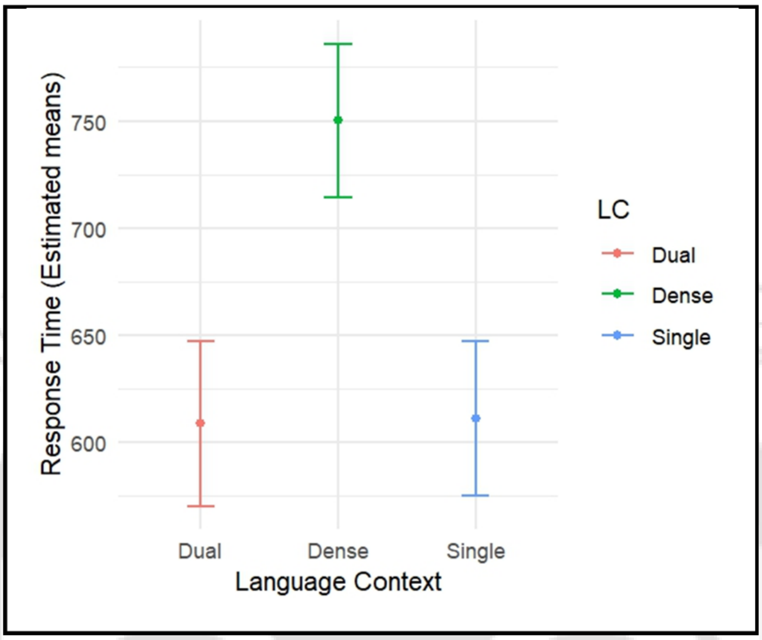


*Figure 4.5.18: Group-wise EM Means performance based on Language Context of overall performance in bivalent task. Dual LC group shows the least EM means, very closely followed by Single LC group, and then Dense CSC group. Bars represent 95% confidence intervals.*

*Pairwise analysis- Language context*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -141.22 | 45.0 | 84.7 | -3.14 | *.007* |
| ***Dense - Single*** | 138.94 | 42.8 | 77.3 | 3.24 | *.005* |
| ***Dual - Single*** | -2.28 | 45.1 | 86.1 | -0.05 | .99 |

*Table 4.5.31: Pair-wise analysis based on Language context of overall performance in bivalent task.*

A pairwise comparison was conducted to examine the differences in performances of the various LC groups *(table 4.5.31)*. The analysis revealed a significant difference between the Dual LC and Dense CSC groups, with Dual LC group being significantly faster than Dense CSC group, with an estimated difference of 141 *ms* (SE = 45.0, df = 84.7, t = −3.14), with $p$ = .007. Similarly, RT of Single LC group was significantly faster than Dense CSC group, with an estimated difference of 138.94 *ms* (SE = 42.8, df = 77.3, t = 3.24). with $p$ = .005.

However, no significant difference was found between the Dual and Single conditions, having an estimated difference of 2.28 *ms* (SE = 45.1, df = 86.1, t = −0.05), with $p$ = .99, suggesting that the performance in these two groups were nearly identical.

Overall, these results indicate that while Dense CSC group had significantly slower response times compared to both the Dual LC and Single LC groups, no significant difference was observed in the performance between the Dual and Single LC groups.

*EM Means- Condition*

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Pure (Colour)*** | 622 | 28.5 | 7.52 | 556 | 689 |
| ***Pure (Shape)*** | 628 | 28.6 | 7.48 | 561 | 695 |
| ***Alternate*** | 691 | 26.4 | 6.75 | 628 | 753 |
| ***Mixed*** | 686 | 26.3 | 6.67 | 624 | 749 |

*Table 4.5.32: Group-wise EM Means based on task condition of overall performance in bivalent task.*

An estimated marginal means (EMM) analysis was conducted to investigate the performance of the participants in the various task conditions *(table 4.5.32)*. Results showed that RTs were shortest in the Pure (Colour) condition with an estimated mean of 622 *ms* (SE = 28.5, df = 7.52, 95% CI [556, 689]). Performance in Pure (Shape) condition came next, with slightly longer RTs of 628 *ms* (SE = 28.6, df = 7.48, 95% CI [561, 695]). Mixed task condition came next, with an estimated mean of 686 *ms* (SE = 26.3, df = 6.67, 95% CI [624, 749]). Finally, Alternate task condition saw the slowest performance, with an estimate of 691 *ms* (SE = 26.4, df = 6.75, 95% CI [628, 753]).

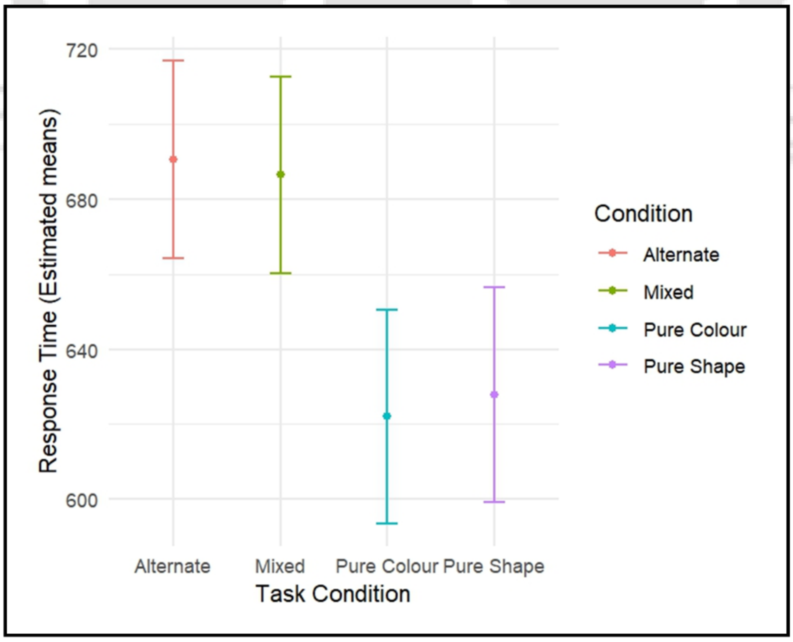


*Figure 4.5.19: Group-wise EM Means performance based on task condition of overall performance in bivalent task. Performance in Pure (Colour) task condition was the fastest, followed closely by Pure (Shape) condition, followed by Mixed condition, and finally Alternate task condition close behind. Bars represent 95% confidence intervals.*

These results suggest that participants had the fastest performance in the Pure task conditions, and the slowest in Alternate task condition, indicating that task complexity or variation may have its influence on response times of the participants *(see figure 4.5.19 for graphical representation)*.

*Pairwise analysis- Task condition*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Pure (Colour) - Pure (Shape)*** | -5.69 | 14.2 | 1684.7 | -0.40 | .98 |
| ***Alternate - Pure (Colour)*** | 68.51 | 13.2 | 52.6 | 5.19 | *< .0001* |
| ***Alternate - Pure (Shape)*** | 62.83 | 13.2 | 44.2 | 4.75 | *.0001* |
| ***Alternate - Mixed*** | 4.14 | 7.90 | 6627.4 | 0.52 | .95 |
| ***Mixed - Pure (Colour)*** | 64.37 | 13.6 | 35.5 | 4.72 | *.0002* |
| ***Mixed - Pure (Shape)*** | 58.68 | 13.7 | 30.7 | 4.28 | *.0009* |

*Table 4.5.33: Pair-wise analysis based on task condition of overall performance in bivalent task.*

A pairwise comparison was conducted to examine the differences in response times between task conditions (Pure (Colour), Pure (Shape), Alternate, and Mixed) *(table 4.5.33)*. The comparison between the Pure (Colour) and Pure (Shape) conditions revealed no significant difference in response times, with an estimate of 5.69 *ms* (SE = 14.2, df = 1684.7, t = −0.40), $p = .98$, indicating that while these two conditions produced similar response times, performance in Pure (Colour) was faster.

However, significant differences were found between the Alternate and Pure (Colour) conditions, where performance in Pure (Colour) was faster by an estimated difference of 68.51 *ms* (SE = 13.2, df = 52.6, t = 5.19), with $p < .0001$. Similarly, between the Alternate and Pure (Shape) conditions, Pure (Shape) showed faster performance, having an estimated difference of 62.83 *ms* (SE = 13.2, df = 44.2, t = 4.75), $p = .0001$. However, when comparing performances in Alternate and Mixed task conditions, Mixed condition did have faster performance, with an estimated difference of 4.14 *ms* (SE = 7.90, df = 6627.4, t = 0.52), $p = .95$, this difference was not significant, indicating that performances were comparable between these two conditions.

Mixed condition showed significantly longer response times compared to Pure (Colour) condition, with an estimate of 64.37 *ms* (SE = 13.6, df = 35.5, t = 4.72), and $p = .0002$, as well as Pure (Shape) condition, with an estimate of 58.68 *ms* (SE = 13.7, df = 30.7, t = 4.28) with $p = .0009$.

Overall, these results indicate that response times were significantly longer in the Alternate and Mixed conditions compared to the Pure (Colour) and Pure (Shape) conditions, but there was no difference between the Alternate and Mixed conditions.

*EM Means- LC * Condition*

| LC | Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Pure (Colour)*** | 559 | 38.9 | 25.2 | 479 | 639 |
| ***Single*** | ***Pure (Shape)*** | 616 | 38.8 | 24.6 | 536 | 696 |
| ***Single*** | ***Alternate*** | 632 | 36.4 | 21.7 | 556 | 707 |
| ***Single*** | ***Mixed*** | 638 | 36.4 | 21.7 | 563 | 714 |
| ***Dual*** | ***Pure (Colour)*** | 593 | 41.4 | 31.6 | 508 | 677 |
| ***Dual*** | ***Pure (Shape)*** | 542 | 41.4 | 31.1 | 458 | 627 |
| ***Dual*** | ***Alternate*** | 655 | 39.1 | 28.0 | 575 | 735 |
| ***Dual*** | ***Mixed*** | 645 | 38.9 | 27.3 | 566 | 725 |
| ***Dense*** | ***Pure (Colour)*** | 715 | 38.7 | 24.8 | 635 | 795 |
| ***Dense*** | ***Pure (Shape)*** | 725 | 38.6 | 24.3 | 645 | 805 |
| ***Dense*** | ***Alternate*** | 785 | 36.3 | 21.5 | 709 | 860 |
| ***Dense*** | ***Mixed*** | 776 | 36.1 | 20.9 | 701 | 851 |

*Table 4.5.34: Group-wise EM Means based on interaction between LC and task condition of overall performance in bivalent task.*

An estimated marginal means (EMM) analysis was conducted to investigate the effect of interaction between LC and task condition on reaction times of the participants *(table 4.5.34)*.

In Pure (Colour) task condition, Single LC group showed fastest performance, with an estimated mean of 559 *ms* (SE = 38.9, df = 25.2, 95% CI [479, 639]). Dual LC group followed with an estimate of 593 *ms* (SE = 41.4, df = 31.6, 95% CI [508, 677]). Dense CSC group had the slowest performance among the three, with an estimate of 715 *ms* (SE = 38.7, df = 24.8, 95% CI [635, 795]).

In Pure (Shape) condition, Dual LC group had the fastest performance, with an estimated mean of 542 *ms* (SE = 41.4, df = 31.1, 95% CI [458, 627]). Single LC group came next, with an estimate of 616 *ms* (SE = 38.8, df = 24.6, 95% CI [536, 696]). Dense CSC had an estimate of 725 *ms* (SE = 38.6, df = 24.3, 95% CI [645, 805]), having the slowest performance among the LC groups.

In Alternate task condition, Single LC group had shortest mean RT, with an estimate of 632 *ms* (SE = 36.4, df = 21.7, 95% CI [556, 707]). Dual LC group closely followed, with an estimate of 655 *ms* (SE = 39.1, df = 28.0, 95% CI [575, 735]). Finally, Dense CSC group came with an estimated mean of 785 *ms* (SE = 36.3, df = 21.5, 95% CI [709, 860]).

Finally, in Mixed task condition, Single LC group outperformed the others with an estimated mean 638 *ms* (SE = 36.4, df = 21.7, 95% CI [563, 714]). Dual LC group followed, with an estimate of 645 *ms* (SE = 38.9, df = 27.3, 95% CI [566, 725]). Dense CSC group had an estimated mean of 776 *ms* (SE = 36.1, df = 20.9, 95% CI [701, 851]).

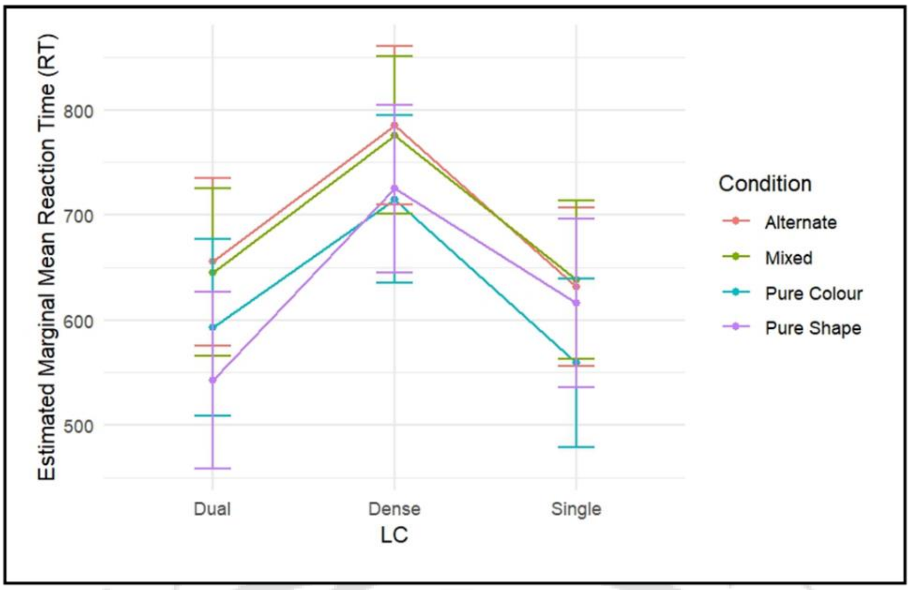


*Figure 4.5.20: Interaction of LC x Task condition of overall performance in bivalent task.*

These results suggest that Single and Dual LC groups alternately showed fastest performance with little variation between task conditions, while Dense CSC group consistently had longer RTs across all task conditions. Task condition wise, Pure task conditions had faster performances, while participants in all LC groups had slowest performance in Alternate task condition *(see figure 4.5.20 for graphical representation)*.

***Accuracy analysis***

*Error rate.* Error-rate analysis revealed that Dual LC group had the least errors (3.22%%), followed by Single LC group (5.19%), and then came Dense CSC group (6.33%).

*GLMM.* A generalized linear mixed model (GLMM) was conducted to examine the effects of linguistic context (LC), task condition, and response time on error rates. The random effects analysis showed that variability in intercepts across participants with a variance of 0.63 (SD = 0.79) and across trial types, having variance of 0.05 (SD = 0.22) was relatively small, suggesting limited between-group variability in error rates.

When comparing performance of various LC groups, when comparing Dual LC group and Single LC group, there was an estimated difference of 0.84 (SE = 0.39, z = 2.19), with $p$ = .03, where Single LC showed significantly lower accuracy rate compared to Dual LC group. However, the difference between other groups showed that Dense CSC group had lower accuracy rate than Dual LC group, and that Single LC group had a lower accuracy rate than Dense CSC group, these differences did not reach statistical significance.

Regarding task condition, the comparison between Alternate and Mixed task conditions showed an estimated difference of 0.56 (SE = 0.30, z = 1.86), with $p = .06$, where the error rate in Mixed condition had lower accuracy than Alternate task condition. Pure (Colour) and Pure (Shape) also had lower accuracy compared to Alternate task condition. Mixed task condition had lower accuracy rate than Pure (Colour) and Pure (Shape) task conditions, whereas Pure (Shape) had lower accuracy than Pure (Colour).

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -3.99 | 0.34 | -11.64 | < *.001* |
| ***LC*** | | | | |
| DLC vs. SLC | 0.84 | .39 | 2.19 | *.03* |
| DLC vs. DCS | 0.67 | 0.39 | 1.69 | *.09* |
| SLC vs. DCS | -0.18 | 0.35 | -0.51 | .61 |
| ***Task condition*** | | | | |
| Alternate vs. Pure (Colour) | 0.06 | 0.39 | 0.16 | .87 |
| Alternate vs. Pure (Shape) | 0.15 | 0.37 | 0.41 | .68 |
| Alternate vs. Mixed | 0.56 | 0.30 | 1.86 | *.06* |
| Pure (Colour) vs. Pure (Shape) | 0.09 | 0.41 | 0.22 | .83 |
| Pure (Colour) vs. Mixed | 0.50 | 0.36 | 1.39 | .16 |
| Pure (Shape) vs. Mixed | 0.41 | 0.34 | 1.21 | .23 |
| ***Response time*** | | | | |
| RT (scaled) | -0.24 | 0.06 | -3.92 | < *.001* |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Alternate vs. Pure (Colour) | -0.70 | 0.49 | -1.44 | .15 |
| DLC vs. DCS: Alternate vs. Pure (Colour) | -0.38 | 0.49 | -0.77 | .44 |
| SLC vs. DCS: Alternate vs. Pure (Colour) | 0.32 | 0.44 | 0.73 | .46 |
| DLC vs. SLC: Alternate vs. Pure (Shape) | -0.16 | 0.45 | -0.36 | .72 |
| DLC vs. DCS: Alternate vs. Pure (Shape) | 0.19 | 0.45 | 0.43 | .67 |
| SLC vs. DCS: Alternate vs. Pure (Shape) | 0.35 | 0.37 | 0.96 | .34 |
| DLC vs. SLC: Alternate vs. Mixed | -0.65 | 0.38 | -1.72 | *.08* |
| DLC vs. DCS: Alternate vs. Mixed | 0.11 | 0.37 | 0.30 | .77 |
| SLC vs. DCS: Alternate vs. Mixed | 0.76 | 0.31 | 2.41 | *.02* |
| DLC vs. SLC: Pure (Colour) vs. Pure (Shape) | 0.54 | 0.52 | 1.04 | .30 |
| DLC vs. DCS: Pure (Colour) vs. Pure (Shape) | 0.57 | 0.52 | 1.09 | .27 |
| SLC vs. DCS: Pure (Colour) vs. Pure (Shape) | 0.03 | 0.47 | 0.07 | .95 |
| DLC vs. SLC: Pure (Colour) vs. Mixed | 0.06 | 0.47 | 0.12 | .91 |
| DLC vs. DCS: Pure (Colour) vs. Mixed | 0.49 | 0.46 | 1.07 | .29 |
| SLC vs. DCS: Pure (Colour) vs. Mixed | 0.44 | 0.43 | 1.07 | .29 |
| DLC vs. SLC: Pure (Shape) vs. Mixed | -0.49 | 0.42 | -1.16 | .25 |
| DLC vs. DCS: Pure (Shape) vs. Mixed | -0.08 | 0.41 | -0.21 | .84 |
| SLC vs. DCS: Pure (Shape) vs. Mixed | 0.40 | 0.35 | 1.14 | .26 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.63 | 0.79 |
| Trial Type | (Intercept) | 0.05 | 0.22 |

*Table 4.5.35: GLMM results of error analysis of overall performance in bivalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

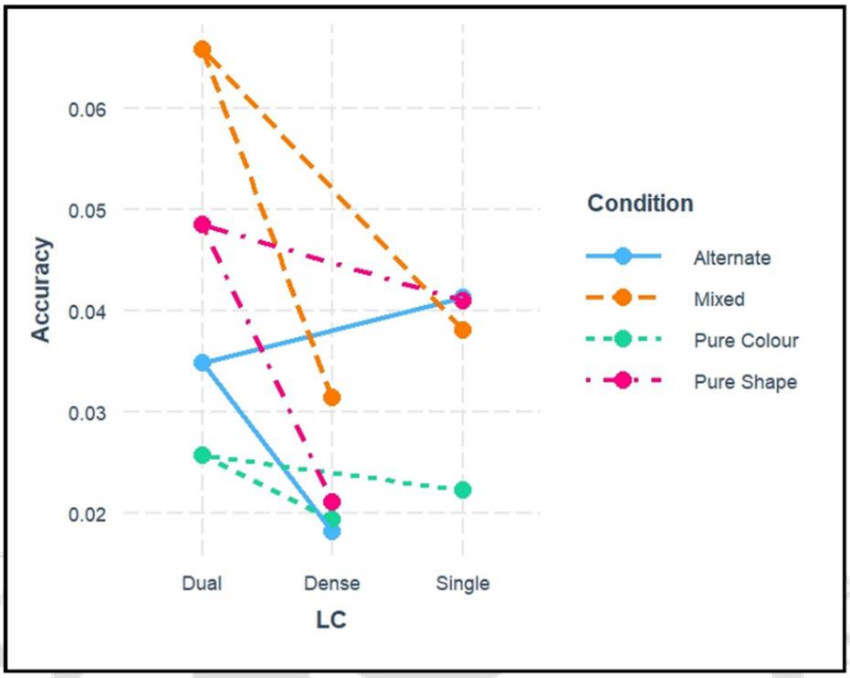


*Figure 4.5.21: Graph showing error analysis of overall performance in bivalent task. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

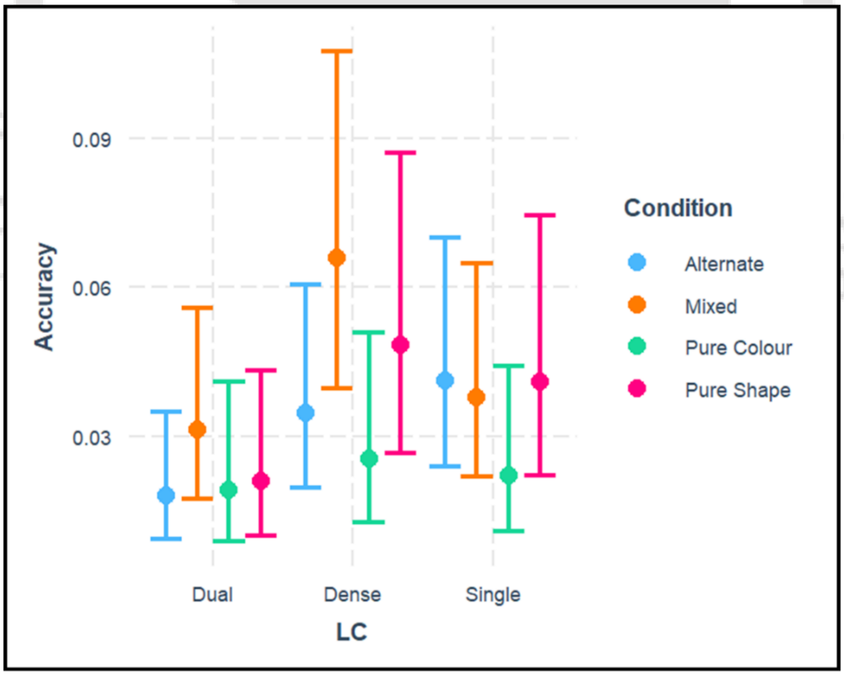


*Figure 4.5.22: Error analysis of each LC group of overall performance in bivalent task. Each coloured bar represents a different task condition.*

On the other hand, response time (scaled) was a significant predictor of error rates, with an estimate of 0.24 (SE = 0.06, z = −3.92), with $p < .001$, indicating that faster response times were associated with more errors. For the interaction between linguistic context and task condition, most of the comparisons were not significant.

In summary, the analysis suggests that linguistic context influences error rates, with lesser errors by Dual LC group than other groups. Task condition had no significant main effect, but response time was a strong predictor, with faster responses associated with fewer errors. Interaction effects between linguistic context and task condition were not significant.

### *Post-error analysis*

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 669.27 | 29.95 | 60.63 | 22.35 | < *.001* |
| Post error | 136.99 | 50.47 | 92.66 | 2.72 | *.008* |
| ***LC*** | | | | | |
| DLC vs. SLC | 17.91 | 40.85 | 57.84 | 0.44 | .66 |
| DLC vs. DCS | 138.31 | 40.87 | 57.94 | 3.38 | *.001* |
| SLC vs. DCS | 120.41 | 39.85 | 58.05 | 3.02 | *.004* |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Colour) | -86.11 | 9.91 | 6809.92 | -8.69 | < *.001* |
| Alternate vs. Pure (Shape) | -56.39 | 9.88 | 6811.26 | -5.71 | < *.001* |
| Alternate vs. Mixed | -5.06 | 8.05 | 6809.93 | -0.63 | .53 |
| Pure (Colour) vs. Pure (Shape) | 29.72 | 11.44 | 6810.15 | 2.60 | *.009* |
| Pure (Colour) vs. Mixed | 81.05 | 9.90 | 6809.60 | 8.19 | < *.001* |
| Pure (Shape) vs. Mixed | 51.32 | 9.87 | 6810.71 | 5.20 | < *.001* |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | -24.61 | 57.36 | 47.01 | -0.43 | .67 |
| Post error: DLC vs. DCS | -100.76 | 56.74 | 45.74 | -1.78 | *.08* |
| Post error: SLC vs. DCS | -76.15 | 52.37 | 38.70 | -1.45 | .15 |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Alternate vs. Pure (Colour) | 81.47 | 52.63 | 3936.77 | 1.55 | .12 |
| Post error: Alternate vs. Pure (Shape) | 122.64 | 45.11 | 3245.02 | 2.72 | *.007* |
| Post error: Alternate vs. Mixed | -23.50 | 38.04 | 3717.42 | -0.62 | .54 |
| Post error: Pure (Colour) vs. Pure (Shape) | 41.17 | 55.84 | 3952.46 | 0.74 | .46 |
| Post error: Pure (Colour) vs. Mixed | -104.97 | 50.12 | 4800.91 | -2.09 | *.04* |
| Post error: Pure (Shape) vs. Mixed | -146.14 | 42.57 | 2829.14 | -3.43 | *.0006* |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Corr** |
| Subject | (Intercept) | 15996 | 126.5 | |
| | Post Error | 12385 | 113.3 | -0.33 |
| Trial Type | (Intercept) | 0 | 0.0 | |
| Residual | | 71230 | 266.9 | |

*Table 4.5.36: LMM results of post-error performance of overall performance in bivalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed-effects model was conducted to examine the effects of post-error adjustments, linguistic context (LC), task condition, and their interactions on response times. The random effects analysis showed significant variability across participants for the intercept, having variance of 15,996 (SD = 126.5) and post-error response, having a variance of 12,385 (SD = 111.3). There was no variance for trial type (Variance = 0). The residual variance was 71,230 (SD = 266.9), indicating notable unexplained variability at the residual level. The correlation (corr = -0.33) indicates a moderate negative relationship, suggesting that participants with higher average RTs tend to exhibit smaller post-error performance difference than participants with lower average RTs.

Post-error responses were significantly slower compared to non-error trials, with an estimated difference of 136.99 *ms* (SE = 50.47, t = 2.72), $p = .008$, indicating a significant post-error slowing effect.

While the interaction between post-error effects and LC was not significant, Dual LC group showed faster post-error performance than Single LC group and Dense CSC group. The difference between Dual LC and Single LC groups had an estimate of 100.76 *ms* (SE = 56.74, t = -1.78), where $p = .08$, which was marginally significant. Single LC group showed faster post-error performance than Dense CSC group, but this difference was not statistically significant.

The interaction between post-error effects and task condition was partly significant, where comparison between some levels showed significance. A significant interaction was found in post-error performance of Alternate and Pure (Shape) condition, with an estimated difference of 122.64 *ms* (SE = 45.11, t = 2.72), $p = .007$, indicating that the post-error slowing effect was greater in Alternate task condition. Alternate condition also showed slower performance than Pure (Colour) condition, Pure (Colour) had slower performance than Pure (Shape), and Mixed task condition had slower performance than Alternate condition, but these differences were not significant. Mixed condition was found to be slower than Pure (Colour), with an estimated difference of 104.97 *ms* (SE = 50.12, t = -2.09), with $p = .04$; as well as Pure (Shape), having an estimated difference of 146.14 *ms* (SE = 42.57, t = -3.43), with $p = .0006$.

In conclusion, the post-error effect was moderated by the interaction between some levels of task condition. However, there was no significant interaction between post-error effects and linguistic context.

### ***Local Switch Cost***

### ***RT analysis***

*Linear Mixed-Model Analysis*

In the linear mixed-model analysis done for local switch cost of bivalent task, Language Context (LC), Trial Type, and Accuracy were the fixed effects. There were 3 levels in LC (Single, Dual and Dense code switching), 4 levels in Trial Type (Repeat A, Mixed A, Repeat M, Mixed M), whereas

Accuracy had 2 levels (Correct and Error). The random effects were participant, display, task, and task condition.

The random effects analysis revealed significant variability across participants, with a variance of 22,434.24 (SD = 149.78), stimulus display had a variance of 698.84 (SD = 26.44), tasks performed had variance of 453.17 (SD=21.29), and task conditions (Variance = 11.96, SD = 3.46). The residual variance was high at 81,045.67 (SD = 284.69), indicating a considerable amount of unexplained variability at the residual level.

| **Fixed effects** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 699.00 | 42.59 | 32.75 | 16.41 | *< .001* |
| ***LC*** | | | | | |
| DLC vs. SLC | -9.28 | 51.71 | 74.65 | -0.18 | .86 |
| DLC vs. DCS | 129.13 | 51.74 | 74.81 | 2.50 | *.01* |
| SLC vs. DCS | 138.40 | 50.50 | 75.22 | 2.74 | *.008* |
| ***Trial type*** | | | | | |
| Repeat A vs Repeat M | -27.48 | 21.99 | 4619.09 | -1.25 | .21 |
| Repeat A vs. Switch A | -11.56 | 20.97 | 4617.16 | -0.55 | .58 |
| Repeat M vs. Switch M | 8.79 | 21.04 | 4617.07 | 0.42 | .68 |
| Switch A vs. Switch M | -7.13 | 21.06 | 4618.36 | -0.34 | .74 |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -11.28 | 42.74 | 4625.16 | -0.26 | .79 |
| ***LC x Trial type interaction*** | | | | | |
| DLC vs. SLC: Repeat A vs. Repeat M | 46.77 | 29.67 | 4617.14 | 1.58 | .12 |
| DLC vs. DCS: Repeat A vs. Repeat M | -13.90 | 29.87 | 4617.31 | -0.47 | .64 |
| SLC vs. DCS: Repeat A vs. Repeat M | -60.67 | 29.27 | 4617.56 | -2.07 | *.04* |
| DLC vs. SLC: Repeat A vs. Switch A | 21.66 | 29.06 | 4617.28 | 0.75 | .46 |
| DLC vs. DCS: Repeat A vs. Switch A | 5.19 | 29.19 | 4617.11 | 0.18 | .86 |
| SLC vs. DCS: Repeat A vs. Switch A | -16.47 | 28.58 | 4617.21 | -0.58 | .57 |
| DLC vs. SLC: Repeat M vs. Switch M | -16.02 | 29.00 | 4616.93 | -0.56 | .58 |
| DLC vs. DCS: Repeat M vs. Switch M | 35.67 | 29.13 | 4617.23 | 1.23 | .22 |
| SLC vs. DCS: Repeat M vs. Switch M | 51.69 | 28.55 | 4617.32 | 1.81 | *.07* |
| DLC vs. SLC: Switch A vs. Switch M | 9.09 | 28.35 | 4617.04 | 0.32 | .75 |
| DLC vs. DCS: Switch A vs. Switch M | 16.58 | 28.45 | 4617.07 | 0.58 | .56 |
| SLC vs. DCS: Switch A vs. Switch M | 7.49 | 27.86 | 4617.14 | 0.27 | .79 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | -85.77 | 53.62 | 4626.16 | -1.60 | .11 |
| DLC vs. DCS: Correct vs. Error | 5.42 | 52.19 | 4635.41 | 0.10 | .92 |
| SLC vs. DCS: Correct vs. Error | 91.18 | 44.21 | 4642.99 | 2.06 | *.04* |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 22434.24 | 149.78 |
| Display | (Intercept) | 698.84 | 26.44 |
| Task | (Intercept) | 453.17 | 21.29 |
| Condition | (Intercept) | 11.96 | 3.46 |
| Residual | | 81045.67 | 284.69 |

*Table 4.5.37: LMM results of RT analysis of local switch cost performance in bivalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context; A: Alternate task condition; M: Mixed task condition).*

The fixed effect of LC significantly affected response times, with participants in the Dense CSC group responding significantly more slowly than those in the Dual LC group, with an estimated difference of 129.13 *ms* (SE = 51.74, df = 74.81, t = 2.50), with *p* = .01. Comparing Single LC group with Dense CSC group showed than Single LC group had a faster performance, with an estimated difference of 138.40 *ms* (SE = 50.50, t = 2.74), with *p* = .008. However, there was no significant difference between Dual LC and Single LC group, where Single LC group showed faster performance.

The main effects of trial type were non-significant. There was no significant difference between performance in Repeat A and Repeat M or between Repeat A and Switch A. Results revealed that Repeat trials had faster performance than Switch trials, and performance in Mixed task condition were faster than Alternate task condition. The main effect of accuracy was also non-significant, with no significant difference in response times between correct and error trials, but the performance in error trials were faster than correct trials. The interaction between LC and trial type also was non-significant across several comparisons. In the interaction between LC and accuracy, comparing performance between Single LC group and Dense CSC group yielded an estimated difference of 91.18 (SE = 44.21, t = 2.06), with *p* = .04, the other comparisons were not significant.

In summary, while language context had a significant effect on response times, with slower responses in the DLC condition compared to the DCS condition, trial type, accuracy, and their interactions with language context did not significantly affect response times.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 925322 | 462661 | 2 | 85.8 | 5.71 | *.005* |
| ***Trial Type*** | 175743 | 58581 | 3 | 4595.3 | 0.72 | .54 |
| ***Accuracy*** | 277810 | 277810 | 1 | 4637.3 | 3.43 | *.06* |
| ***LC: Trial Type*** | 502333 | 83722 | 6 | 4617.2 | 1.03 | .40 |
| ***LC: Accuracy*** | 391979 | 195989 | 2 | 4635.6 | 2.42 | *.09* |

*Table 4.5.38: Type III Analysis of Variance Table with Satterthwaite's method of local switch cost performance in bivalent task.*

A Type III analysis of variance (ANOVA) using Satterthwaite's method was conducted to examine the effects of linguistic context (LC), trial type, accuracy, and their interactions on response times. The results revealed a significant main effect of LC, F(2, 85.8) = 5.71, *p* = .005, indicating that response times significantly differed across the three language context groups. However, no significant main effect of trial type was found, F(3, 4595.3) = 0.72, *p* = .54, suggesting that participants' reaction times did not vary significantly across trial types.

Although the main effect of accuracy approached significance, F(1, 4637.3) = 3.43, $p$ = .06, suggesting that correct versus error responses significantly impacted the RTs in this model. The interaction between LC and accuracy was marginally significant, F(2, 4635.6) = 2.42, $p$ = .09, indicating that only marginally significant interaction occurs between linguistic context and accuracy in predicting response times. The interaction between LC and trial type, however, was not significant, F(6, 4617.2) = 1.03, $p$ = .40, indicating that the effect of language context on response times did not vary across different trial types.

In summary, while linguistic context had a significant main effect on response times, accuracy and its interaction with LC was marginally significant, but trial type, and its interaction with linguistic context did not show significant effects.

### ***Post-HOC analysis***

*EM Means- Language context*

An estimated marginal means (EM means) analysis was conducted to examine the effect of language context (LC) on response times *(table 4.5.39)*. The results showed that the Single LC group had the fastest performance, with an estimated average of 652 *ms* (SE = 41.7, df = 32.1, 95% CI [567, 736]). They were followed by Dual LC group, with an estimated mean of 679 *ms* (SE = 45.2, df = 42.3, 95% CI [588, 770]). The Dense CSC group had the highest average response time of 814 *ms* (SE = 41.2, df = 30.6, 95% CI [730, 898]).

These results suggest that Single LC group had the fastest performance, followed by Dual LC group, with Dense CSC group showing the slowest response times overall *(see figure 4.5.23 for graphical representation)*.

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 652 | 41.7 | 32.1 | 567 | 736 |
| ***Dual*** | 679 | 45.2 | 42.3 | 588 | 770 |
| ***Dense*** | 814 | 41.2 | 30.6 | 730 | 898 |

*Table 4.5.39: Group-wise EM Means based on Language Context of local switch cost performance in bivalent task.*

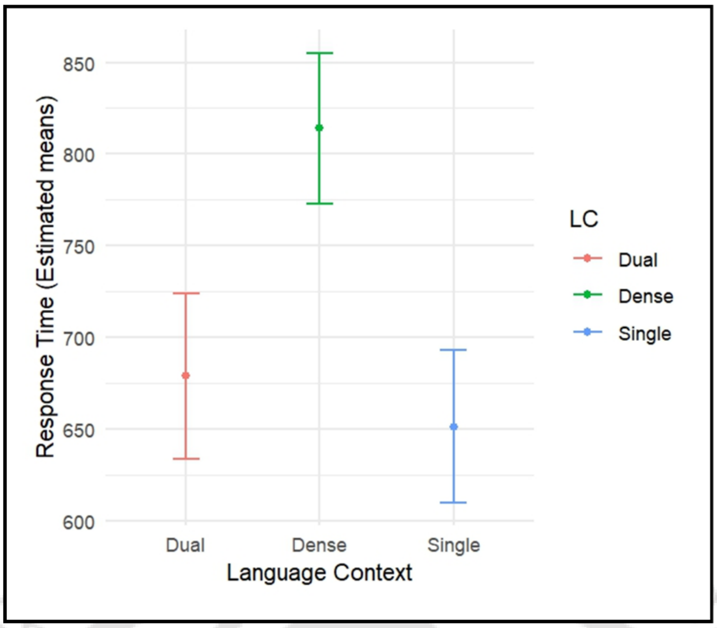


*Figure 4.5.23: Group-wise EM Means performance based on Language Context of local switch cost performance in bivalent task. In this case, Single LC group shows the least EM means, followed by Dual LC group, and then Dense CSC group. Bars represent 95% confidence intervals.*

*Pairwise analysis- Language context*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -135.1 | 54.1 | 89.1 | -2.50 | *.04* |
| ***Dense - Single*** | 162.5 | 51.2 | 79.2 | 3.18 | *.006* |
| ***Dual - Single*** | 27.4 | 54.4 | 91.7 | 0.50 | .87 |

*Table 4.5.40: Pair-wise analysis based on Language context of local switch cost performance in bivalent task.*

A pairwise comparison analysis was conducted to examine the differences in response times among the various language context groups *(table 4.5.40)*. The comparison between the Dual LC group and Dense CSC group revealed a significant difference, with the estimate indicating that response times of Dual LC group was approximately 135.1 *ms* faster than that of Dense CSC group (SE = 54.1, df = 89.1, t = −2.50), $p$ = .04. When comparing Dense CSC group with Single LC group, the average RT of Dense CSC group were significantly longer, with an estimate of 162.5 *ms* (SE = 51.2, df = 79.2, t = 3.18), with $p$ = .006.

However, the comparison between the Dual LC group and Single LC showed no significant difference, with an estimate of 27.4 *ms* (SE = 54.4, df = 91.7, t = 0.50), $p$ = .87, thus indicating that response times did not significantly differ between the Dual and Single LC groups.

In summary, the Dense CSC group had significantly slower response times compared to both the DLC and SLC conditions, while no significant difference was found between the Dual LC group and Single LC group.

*EM Means- Trial type*

| Trial Type | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Repeat A*** | 720 | 30.7 | 11.8 | 653 | 787 |
| ***Repeat M*** | 703 | 30.6 | 11.7 | 637 | 770 |
| ***Switch A*** | 717 | 30.7 | 11.9 | 650 | 784 |
| ***Switch M*** | 719 | 30.6 | 11.7 | 652 | 786 |

*Table 4.5.41: Group-wise EM Means based on trial type of local switch cost performance in bivalent task. (A: Alternate task condition; M: Mixed task condition).*

An estimated marginal means (EM means) analysis was conducted to evaluate the effect of trial type on response times *(table 4.5.41)*. The results indicated that the performance in Repeat trials of Mixed task condition was fastest, with an average response of 703 *ms* (SE = 30.6, df = 11.7, 95% CI [637, 770]). This was followed by performance in Switch trials of Alternate task condition, having an average estimate of 717 *ms* (SE = 30.7, df = 11.9, 95% CI [650, 784]). The Switch trials in Mixed task condition followed closely behind, with an average RT of 719 *ms* (SE = 30.6, df = 11.7, 95% CI [652, 786]). Finally, the Repeat trials of Alternate task condition followed with slightly higher average mean of 720 *ms* (SE = 30.7, df = 11.8, 95% CI [653, 787]).

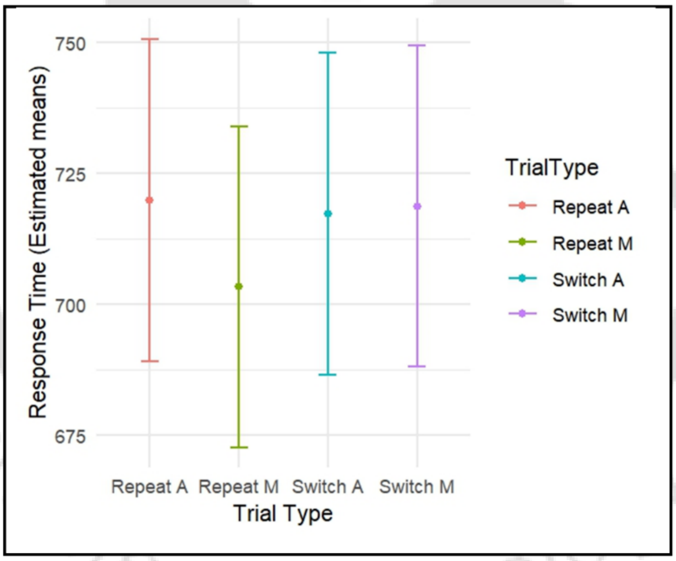


*Figure 4.5.24: Group-wise EM Means performance based on trial types of local switch cost performance in bivalent task. Performance in Repeat trials in Mixed condition was fastest, followed by Switch trials in Alternate condition, closely followed by Switch trials in Mixed, then Repeat trials in Alternate task condition. Bars represent 95% confidence intervals. (A: Alternate task condition; M: Mixed task condition).*

These findings suggest while performance in Repeat M trials were fastest, there was no substantial differences observed among the performances in Repeat A, Repeat M, Switch A, and Switch M trial types. Overall, the average response times indicate a consistent pattern across different trial types *(see figure 4.5.24 for graphical representation)*.

*Pairwise analysis- Trial type*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Repeat A – Repeat M*** | 16.52 | 13.1 | 6234 | 1.26 | .59 |
| ***Repeat A – Switch A*** | 2.61 | 11.8 | 4617 | 0.22 | .99 |
| ***Repeat M – Switch M*** | -15.34 | 12.1 | 4535 | -1.27 | .58 |
| ***Switch A – Switch M*** | -1.43 | 12.6 | 6416 | -0.11 | .99 |

*Table 4.5.42: Pair-wise analysis based on trial type of local switch cost performance in bivalent task. (A: Alternate task condition; M: Mixed task condition).*

A pairwise comparison analysis was conducted to examine the differences in response times across trial types *(table 4.5.42)*. The comparison between the Repeat trials of Alternate and Mixed task condition, with an estimated difference of 16.52 *ms* (SE = 13.1, df = 6234, t = 1.26), *p* = .59, where performance in Mixed condition was faster, but not significantly so. Similarly, between Switch trials of Alternate and Mixed task conditions, there was an estimated difference of 1.43 *ms* (SE = 12.6, df = 6416, t = 0.11), p = .99, where performance in Alternate task condition was faster, indicating that participants' response times in these trials were comparable.

The analysis of response times between Repeat and Switch trials of Alternate task condition also showed no significant difference, with an estimate of 2.61 *ms* (SE = 11.8, df = 4617, t = 0.22), *p* = .99, with the performance in Switch trials being faster. Similarly, the comparison between Repeat and Switch trials of Mixed task condition demonstrated no significant difference in response times, yielding an estimate of 15.34 *ms* (SE = 12.1, df = 4535, t = -1.27), but *p* = .58, where the repeat trials showed faster performance.

Overall, these findings suggest that there were no significant differences in response times among the various trial types, indicating a consistent pattern of performance across task conditions.

*EM Means- LC * Trial type*

| LC | Trial Type | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Repeat A*** | 641 | 43.4 | 37.9 | 553 | 729 |
| ***Single*** | ***Switch A*** | 651 | 43.6 | 38.4 | 563 | 739 |
| ***Single*** | ***Repeat M*** | 660 | 43.6 | 38.5 | 572 | 749 |
| ***Single*** | ***Switch M*** | 653 | 43.5 | 38.1 | 565 | 741 |
| ***Dual*** | ***Repeat A*** | 693 | 47.1 | 49.8 | 599 | 788 |
| ***Dual*** | ***Switch A*** | 682 | 47.4 | 51.0 | 587 | 777 |
| ***Dual*** | ***Repeat M*** | 666 | 46.8 | 48.7 | 572 | 760 |
| ***Dual*** | ***Switch M*** | 675 | 46.9 | 49.2 | 580 | 769 |
| ***Dense*** | ***Repeat A*** | 825 | 43.4 | 37.6 | 737 | 913 |
| ***Dense*** | ***Switch A*** | 819 | 43.2 | 37.0 | 731 | 906 |
| ***Dense*** | ***Repeat M*** | 784 | 42.9 | 36.1 | 697 | 871 |
| ***Dense*** | ***Switch M*** | 828 | 42.9 | 36.2 | 741 | 915 |

*Table 4.5.43: Group-wise EM Means based on interaction between LC and trial type of local switch cost performance in bivalent task. (A: Alternate task condition; M: Mixed task condition).*

An estimated marginal means (EM means) analysis was performed to assess the interaction between linguistic context (LC) and trial type on response times *(table 4.5.43)*.

In the Repeat trials of Alternate task condition, Single LC group had the fastest performance, with an average mean RT of 641 *ms* (SE = 43.4, df = 37.9, 95% CI [553, 729]). Dual LC group followed, with an estimated mean of 693 *ms* (SE = 47.1, df = 49.8, 95% CI [599, 788]). Dense CSC group came at the end with an average mean RT of 825 *ms* (SE = 43.4, df = 37.6, 95% CI [737, 913]).

In the Switch trials of Alternate task condition, Single LC group had lowest average mean performance of 651 *ms* (SE = 43.6, df = 38.4, 95% CI [563, 739]). Dual LC group came next, with an average performance of 682 *ms* (SE = 47.4, df = 51.0, 95% CI [587, 777]). Dense CSC group had an average performance of 819 *ms* (SE = 43.2, df = 37.0, 95% CI [731, 906]).

The Repeat trials in Mixed task condition saw Single LC group give the fastest performance, with an average RT of 660 *ms* (SE = 43.6, df = 38.5, 95% CI [572, 749]). Dual LC group followed closely, with an average estimate of 666 *ms* (SE = 46.8, df = 48.7, 95% CI [572, 760]). Dense CSC group had the slowest performance, with an average of 784 *ms* (SE = 42.9, df = 36.1, 95% CI [697, 871]).

The Switch trials in Mixed task condition had Single LC group show the fastest performance among the three groups, with an estimated average of 653 *ms* (SE = 43.5, df = 38.1, 95% CI [565, 741]). Dual LC group showed an estimated mean of 675 *ms* (SE = 46.9, df = 49.2, 95% CI [580, 769]). Dense CSC group had the slowest average mean performance with an estimate of 828 *ms* (SE = 42.9, df = 36.2, 95% CI [741, 915]).

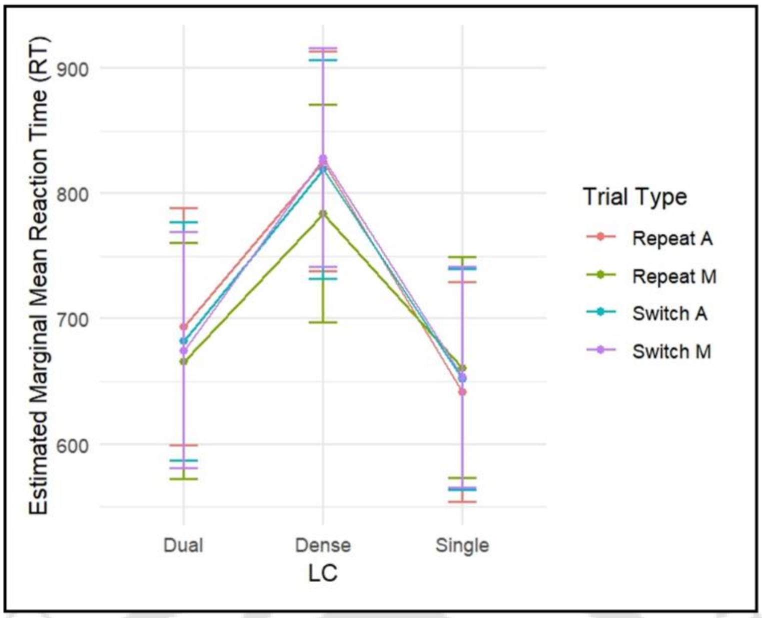


*Figure 4.5.25: Interaction of LC x Task condition of local switch cost performance in bivalent task. (A: Alternate task condition; M: Mixed task condition).*

These results indicate that response times varied significantly across linguistic contexts and trial types. Single LC group consistently outperformed the other groups, Dual LC group followed closely. Dense CSC group consistently showed slowest performance among the three groups *(see figure 4.5.25 for graphical representation)*.

***Accuracy analysis***

*Error rate.* Error-rate analysis revealed that Dual LC group had the least errors (3.15%%), followed by Single LC group (5.20%), and then came Dense CSC group (6.80%).

*GLMM.* A generalized linear mixed model (GLMM) analysis was conducted to investigate the effects of linguistic context (LC) and trial type on error rates. The model included random intercepts for participants, resulting in a variance of 0.51 (SD = 0.71), indicating variability in error rates across individuals. The fixed effects included the intercept, LC, and trial types.

For the fixed effect of LC, the differences between the levels were not statistically significant. Dual LC group had a higher accuracy rate than Single LC group and Dense CSC group. Dense CSC group had a lower accuracy rate than Single LC group.

Regarding trial types, the comparison between Repeat A and Repeat M indicated a significant result, with an estimate of 0.72 (SE = 0.38, z = 1.90), $p$ = .06, suggesting a potential difference in error rates, with Repeat trials in Mixed task condition having significantly lower accuracy rate. In contrast, the other comparisons showed no statistical significance. Repeat trials of Alternate task condition had lower accuracy than Switch trials of Alternate task condition. Similarly, the Repeat trials of

Mixed task condition had lower accuracy than Switch trials of Mixed task condition. The Switch trials of Mixed task condition had a lower accuracy rate than Switch trials of Alternate task condition.

Additionally, the analysis of scaled reaction times did not reveal a significant effect, having an estimate of 0.10 (SE = 0.07, z = −1.41), $p = .16$. The interaction effects of LC and trial type were also examined; however, most did not reach significance, suggesting no substantial effect of language context on the accuracy in trial type performance.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -3.68 | 0.35 | -10.59 | < *.001* |
| ***LC*** | | | | |
| DLC vs. SLC | 0.74 | 0.43 | 1.70 | *.09* |
| DLC vs. DCS | 0.19 | 0.46 | 0.40 | .69 |
| SLC vs. DCS | -0.56 | 0.41 | -1.37 | .17 |
| ***Trial type*** | | | | |
| Repeat A vs Repeat M | 0.72 | 0.38 | 1.90 | *.06* |
| Repeat A vs. Switch A | -0.61 | 0.50 | -1.22 | .22 |
| Repeat M vs. Switch M | -0.93 | 0.39 | -2.40 | *.02* |
| Switch A vs. Switch M | 0.40 | 0.51 | 0.78 | .43 |
| ***Response time*** | | | | |
| RT (scaled) | -0.10 | 0.07 | -1.41 | .16 |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Repeat A vs Repeat M | -0.59 | 0.48 | -1.23 | .22 |
| DLC vs. DCS: Repeat A vs Repeat M | 0.49 | 0.49 | 0.99 | .32 |
| SLC vs. DCS: Repeat A vs Repeat M | 1.07 | 0.43 | 2.51 | *.01* |
| DLC vs. SLC: Repeat A vs. Switch A | 0.37 | 0.59 | 0.63 | .53 |
| DLC vs. DCS: Repeat A vs. Switch A | 1.02 | 0.61 | 1.67 | *.09* |
| SLC vs. DCS: Repeat A vs. Switch A | 0.64 | 0.46 | 1.39 | .16 |
| DLC vs. SLC: Repeat M vs. Switch M | 0.25 | 0.51 | 0.49 | .62 |
| DLC vs. DCS: Repeat M vs. Switch M | 0.20 | -.47 | 0.43 | .67 |
| SLC vs. DCS: Repeat M vs. Switch M | -0.05 | 0.42 | -0.11 | .91 |
| DLC vs. SLC: Switch A vs. Switch M | -0.71 | 0.61 | -1.16 | .25 |
| DLC vs. DCS: Switch A vs. Switch M | -0.33 | 0.59 | -0.55 | .58 |
| SLC vs. DCS: Switch A vs. Switch M | 0.38 | 0.45 | 0.84 | .40 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.51 | 0.71 |
| Condition | (Intercept) | 0.00 | 0.00 |

*Table 4.5.44: GLMM results of error analysis of local switch cost performance in bivalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context; A: Alternate task condition; M: Mixed task condition).*

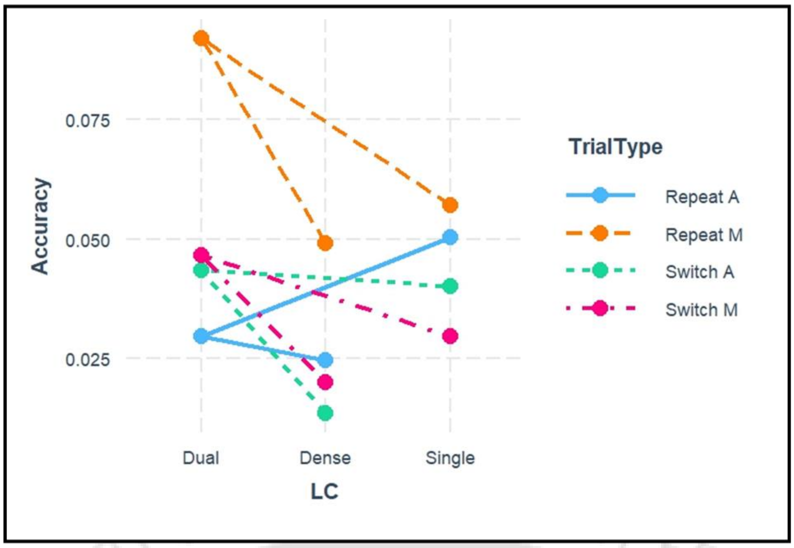


*Figure 4.5.26: Graph showing error analysis of local switch cost performance in bivalent task. The lines connect the different LC groups across the different trial types in various task conditions, showing respective rates of accuracy. (A: Alternate task condition; M: Mixed task condition).*

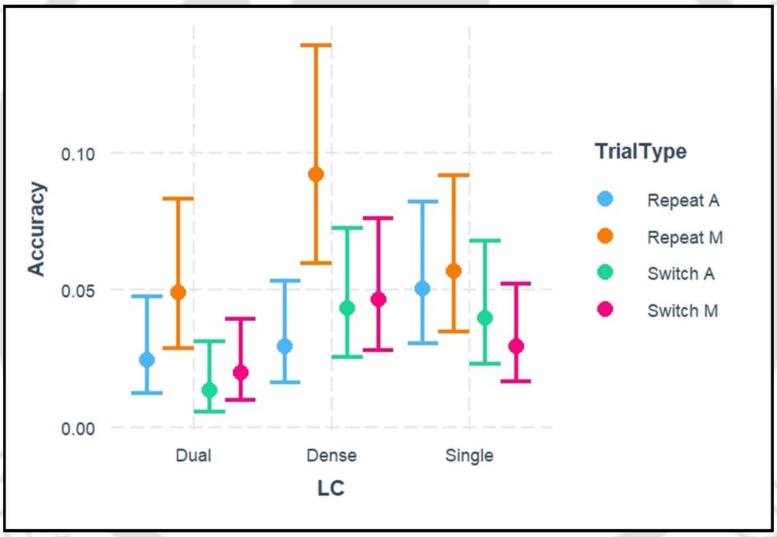


*Figure 4.5.27: Error analysis of each LC group of local switch cost performance in bivalent task. Each coloured bar represents a different trial type. (A: Alternate task condition; M: Mixed task condition).*

Overall, while some estimates approached significance, the results indicate that neither the linguistic context nor trial type significantly influenced error rates in this analysis *(see figure 4.5.26, 4.5.27 for graphical representation)*.

### *Post-error analysis*

A linear mixed model (LMM) analysis was conducted to assess the impact of post-error conditions on response times, while accounting for random effects associated with participants and conditions. The random effects analysis indicated significant variability in intercepts for participant variations, with a variance of 22.426 (SD = 149.75), and post-error responses had a variance of 18,089 (SD = 134.50).

| *Fixed effects* | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 687.3 | 89.32 | 0.00 | 7.70 | *1.00* |
| Post error | 102.0 | 70.77 | 133.90 | 1.44 | .15 |
| ***LC*** | | | | | |
| DLC vs. SLC | 6.52 | 448.55 | 57.77 | 0.13 | .89 |
| DLC vs. DCS | 137.70 | 48.57 | 57.87 | 2.84 | *.006* |
| SLC vs. DCS | 131.17 | 47.37 | 57.99 | 2.77 | *.008* |
| ***Trial type*** | | | | | |
| Repeat A vs Repeat M | -17.67 | 116.3 | 0.00 | -0.15 | 1.00 |
| Repeat A vs. Switch A | -5.25 | 12.04 | 4577.0 | -0.44 | .66 |
| Repeat M vs. Switch M | 12.31 | 12.08 | 4576.77 | 1.02 | .31 |
| Switch A vs. Switch M | -0.12 | 116.27 | 4576.42 | -0.001 | .99 |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | 36.12 | 71.73 | 49.36 | 0.50 | .62 |
| Post error: DLC vs. DCS | -113.60 | 71.60 | 45.00 | -1.59 | .12 |
| Post error: SLC vs. DCS | -149.74 | 65.06 | 36.42 | -2.30 | *.03* |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Repeat A vs Repeat M | -53.42 | 66.28 | 2749.0 | -0.81 | .42 |
| Post error: Repeat A vs. Switch A | 31.89 | 61.33 | 2730.0 | 0.52 | .60 |
| Post error: Repeat M vs. Switch M | 108.18 | 56.63 | 2775.21 | -1.91 | *.06* |
| Post error: Switch A vs. Switch M | 22.88 | 51.50 | 2064.09 | -0.44 | .66 |

| *Random effects* | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Corr** |
| Subject | (Intercept) | 22426 | 149.8 | |
| | Post Error | 18089 | 134.5 | -0.38 |
| Condition | (Intercept) | 236505 | 486.3 | |
| Residual | | 80685 | 284.1 | |

*Table 4.5.45: LMM results of post-error performance of local switch cost performance in bivalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context; A: Alternate task condition; M: Mixed task condition).*

The effect of post-error did not reach significance, with an estimate of 102.0 *ms* (SE = 70.77, t = 1.44), where $p$ = .15. This indicated that causing errors did not have any significant effect on the subsequent performance of the participants.

The interaction between post-error performance and LC group saw statistically significant in comparing post-error performance of Dense CSC group and Single LC group, having an estimated difference of 149.74 *ms* (SE = 65.06, t = -2.30), with $p$ = .03, where performance in Dense CSC group was slower. Single LC group also had faster post-error performance than Dual LC group, however, this difference was not significant. Dual LC group showed faster performance than Dense CSC group, but this was also not significant.

Analysis of the interaction between post-error performance and task condition showed statistically significant difference between Switch and Repeat trials of Mixed task condition, with an estimated difference of 108.18 *ms* (SE = 56.18, t = -1.91), with $p$ = .06, where performance in Switch trials were slower than Repeat trials. Other differences were not statistically significant. For instance, the

Repeat trials of Mixed condition showed slower performance than Alternate condition. On the other hand, the Switch trials of Alternate condition were slower than Switch trials of Mixed condition. In the Alternate task condition, the Repeat trials showed slower performance than Switch trials.

In conclusion, the interaction between post-error performance and the fixed effects of LC and task condition levels showed significance for only few comparisons.

### Global Switch Cost

#### RT analysis

*Linear Mixed-Model Analysis*

For the fixed effect of LC, the comparison of the Dual LC group with Dense CSC group showed a significant effect, with participants demonstrating longer response times in the Dense CSC group, with an estimated difference of 135.48 *ms* (SE = 42.84, t = 3.16), $p = .002$. The difference between Single LC group and Dense CSC group was similarly significant, with an estimated difference of 137.24 *ms* (SE = 41.80, t = 3.28), with $p = .002$, where Single LC group showed faster performance. Conversely, comparing performances of Dual LC group with Single LC group did not yield a significant difference, and showed Dual LC group having marginally slower performance than Single LC group.

For the fixed effect of task conditions, the analysis indicated that participants responded significantly faster in the Pure (Colour) condition compared to Alternate condition, with an estimated difference of 52.62 *ms* (SE = 19.52, t = −2.70), $p = .007$. Other task condition comparisons similarly show statistical significance, for instance, when comparing Pure (Shape) with Mixed task condition, an estimated difference of 102.77 *ms* (SE = 19.67, t = 5.22) was revealed, with $p < .001$, where performance in Pure (Shape) was faster than Mixed task condition. However, the comparison between the Alternate and Mixed conditions was not significant, with an estimate of 12.77 *ms* (SE = 19.07, t = −0.67), and $p = .50$, showing that even though Mixed condition showed faster performance, the difference in performance was not significant.

In terms of accuracy, participants demonstrated significantly slower response times for correct responses as compared to performance in errors, with an estimated difference of 85.95 *ms* (SE = 35.27, t = −2.44), $p = .01$. Interactions between linguistic context and task conditions showed a significant effect for certain levels, such as, for Dual LC group versus Single LC group in the

Alternate versus Pure (Shape) comparison had an estimated difference of 98.10 *ms* (SE = 25.73, t = 3.81), $p < .0001$. Several other interaction comparisons did not reach statistical significance.

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 678.16 | 39.28 | 8.60 | 17.27 | *< .001* |
| ***LC*** | | | | | |
| DLC vs. SLC | -1.76 | 42.79 | 77.88 | -0.04 | 0.97 |
| DLC vs. DCS | 135.48 | 42.84 | 78.24 | 3.16 | *0.002* |
| SLC vs. DCS | 137.24 | 41.80 | 78.57 | 3.28 | *0.002* |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Colour) | -52.62 | 19.52 | 4103.11 | -2.70 | *0.007* |
| Alternate vs. Pure (Shape) | -115.54 | 19.26 | 4085.40 | -6.00 | *< .001* |
| Alternate vs. Mixed | -12.77 | 19.07 | 4404.01 | -0.67 | 0.50 |
| Pure (Colour) vs. Pure (Shape) | -62.92 | 21.39 | 2344.39 | -2.94 | *0.003* |
| Pure (Colour) vs. Mixed | 39.85 | 19.88 | 4147.06 | 2.01 | *0.05* |
| Pure (Shape) vs. Mixed | 102.77 | 19.67 | 4088.66 | 5.22 | *< .001* |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -85.95 | 35.27 | 4411.43 | -2.44 | *0.01* |
| ***LC x Condition interaction*** | | | | | |
| DLC vs. SLC: Alternate vs. Pure (Colour) | -6.43 | 25.97 | 4401.63 | -0.25 | 0.80 |
| DLC vs. DCS: Alternate vs. Pure (Colour) | -21.93 | 26.21 | 4401.96 | -0.84 | 0.40 |
| SLC vs. DCS: Alternate vs. Pure (Colour) | -15.50 | 25.57 | 4402.10 | -0.61 | 0.54 |
| DLC vs. SLC: Alternate vs. Pure (Shape) | 98.10 | 25.73 | 4401.78 | 3.81 | *0.0001* |
| DLC vs. DCS: Alternate vs. Pure (Shape) | 45.31 | 25.91 | 4402.02 | 1.75 | *0.08* |
| SLC vs. DCS: Alternate vs. Pure (Shape) | -52.79 | 25.43 | 4402.29 | -2.08 | *0.04* |
| DLC vs. SLC: Alternate vs. Mixed | 31.34 | 26.38 | 4401.51 | 1.19 | 0.23 |
| DLC vs. DCS: Alternate vs. Mixed | -17.47 | 26.60 | 4402.07 | -0.66 | 0.51 |
| SLC vs. DCS: Alternate vs. Mixed | -48.81 | 26.05 | 4402.32 | -1.87 | *0.06* |
| DLC vs. SLC: Pure (Colour) vs. Pure (Shape) | 104.53 | 25.88 | 4401.57 | 4.04 | *< .001* |
| DLC vs. DCS: Pure (Colour) vs. Pure (Shape) | 67.24 | 26.05 | 4401.29 | 2.58 | *0.01* |
| SLC vs. DCS: Pure (Colour) vs. Pure (Shape) | -37.29 | 25.54 | 4401.71 | -1.46 | 0.14 |
| DLC vs. SLC: Pure (Colour) vs. Mixed | 37.77 | 26.53 | 4401.39 | 1.42 | 0.15 |
| DLC vs. DCS: Pure (Colour) vs. Mixed | 4.47 | 26.74 | 4401.36 | 0.17 | 0.87 |
| SLC vs. DCS: Pure (Colour) vs. Mixed | -33.31 | 26.16 | 4401.52 | -1.27 | 0.20 |
| DLC vs. SLC: Pure (Shape) vs. Mixed | -66.76 | 26.30 | 4401.76 | -2.54 | *0.01* |
| DLC vs. DCS: Pure (Shape) vs. Mixed | -62.78 | 26.38 | 4401.28 | -2.38 | *0.02* |
| SLC vs. DCS: Pure (Shape) vs. Mixed | 3.98 | 25.94 | 4401.85 | 0.15 | 0.88 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | -28.58 | 45.07 | 4418.11 | -0.63 | 0.53 |
| DLC vs. DCS: Correct vs. Error | -9.41 | 45.73 | 4440.91 | -0.21 | 0.84 |
| SLC vs. DCS: Correct vs. Error | 19.17 | 40.45 | 4450.62 | 0.47 | 0.64 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| **Subject** | (Intercept) | 14892.4 | 122.03 |
| **Display** | (Intercept) | 409.2 | 20.23 |
| **Task** | (Intercept) | 961.7 | 31.01 |
| **Residual** | | 63059 | 251.12 |

*Table 4.5.46: LMM results of RT analysis of global switch cost performance in bivalent task. (DCS: Dense code-switching; DL: Dual-language context; SL: Single-language context).*

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 699339 | 349669 | 2 | 89.5 | 5.55 | *.005* |
| ***Condition*** | 4174341 | 1391447 | 3 | 1933.1 | 22.07 | < *.001* |
| ***Accuracy*** | 1909092 | 1909092 | 1 | 4437.5 | 30.27 | < *.001* |
| ***LC: Condition*** | 1470578 | 245096 | 6 | 4401.7 | 3.89 | *.0007* |
| ***LC: Accuracy*** | 28452 | 14226 | 2 | 4437.2 | 0.23 | .80 |

*Table 4.5.47: Type III Analysis of Variance Table with Satterthwaite's method of global switch cost performance in bivalent task.*

A Type III Analysis of Variance (ANOVA) was conducted to examine the effects of LC, condition, and accuracy on the participants' reaction times. The results revealed significant main effects for all factors included in the model.

First, the analysis indicated a significant effect of LC, F(2, 89.5) = 5.55, *p* = .005, suggesting that different language contexts groups performed significantly differently on their responses. Task condition also had a significant impact, with F(3, 1933.1) = 22.07, *p* < .001, indicating that different task conditions significantly influenced the results. Accuracy also emerged as another significant factor, with the analysis yielding F(1, 4437.5) = 30.27, *p* < .001, thus highlighting the importance of accuracy in determining performance outcomes.

Additionally, the interaction between linguistic context and condition was also significant, F(6, 4401.7) = 3.89, *p* = .0007, indicating that the effects of linguistic context varied across different conditions. However, the interaction between linguistic context and accuracy was not significant, F(2, 4437.2) = 0.23, *p* = .80, suggesting that accuracy did not significantly modify the relationship between linguistic context and the dependent variable.

Thus, with the exception of interaction between language context and accuracy, which did not show statistical significance, all other factors and interactions showed statistical significance.

### ***Post-HOC analysis***

*EM Means- Language context*

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 605 | 38.6 | 8.06 | 516 | 693 |
| ***Dual*** | 590 | 40.9 | 10.17 | 499 | 681 |
| ***Dense*** | 722 | 38.7 | 8.14 | 633 | 811 |

*Table 4.5.48: Group-wise EM Means based on Language Context of global switch cost performance in bivalent task.*

An analysis of estimated marginal means (EM means) was conducted to evaluate the effects of language context (LC) on the dependent variable of RT *(table 4.5.48)*. The results indicated that participants in the Dual LC group had the fastest performance with an estimated mean of 590 *ms* (SE = 40.9, df = 10.17, 95% CI [499, 681]). Single LC group had a mean score of 605 *ms* (SE =

38.6, df = 8.06, 95% CI [516, 693]). Dense CSC group yielded the highest mean score of 722 *ms* (SE = 38.7, df = 8.14, 95% CI [633, 811]).

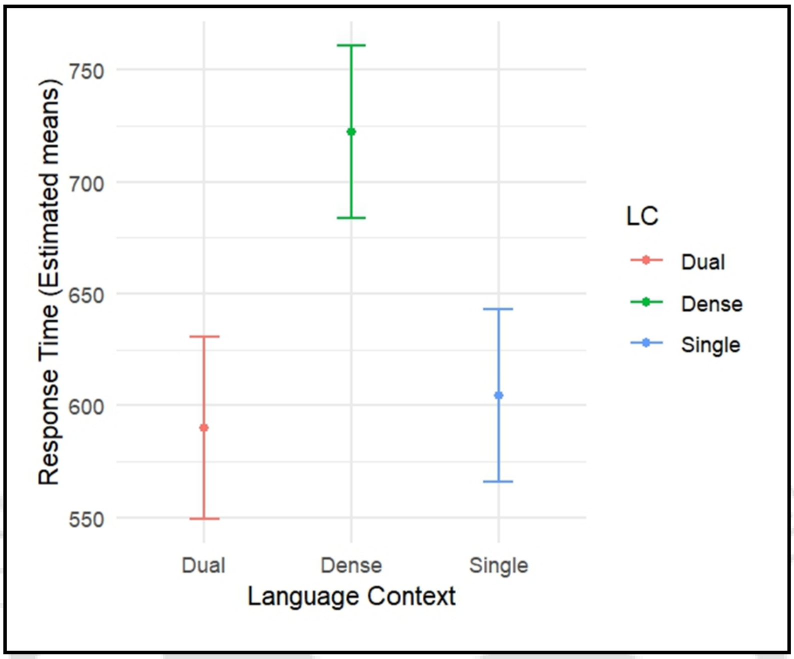


*Figure 4.5.28: Group-wise EM Means performance based on Language Context of global switch cost performance in bivalent task. Dual LC group shows the least EM means, closely followed by Single LC group, and then Dense CSC group. Bars represent 95% confidence intervals.*

Thus, these findings show that Dual LC group had the fastest mean performance, followed by Single LC group and then came Dense CSC group at the end with the slowest mean performance *(see figure 4.5.28 for graphical representation)*.

*Pairwise analysis- Language context*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -132.3 | 44.8 | 92.9 | -2.96 | *0.01* |
| ***Dual - Single*** | -14.7 | 44.7 | 92.4 | -0.33 | 0.94 |
| ***Dense - Single*** | 117.6 | 42.6 | 84.4 | 2.76 | *0.02* |

*Table 4.5.49: Pair-wise analysis based on Language context of global switch cost performance in bivalent task.*

A pairwise contrast analysis was conducted to examine differences in performance between various linguistic contexts (LC) *(table 4.5.49)*. The comparison between the Dual LC group and Dense CSC group revealed a significant difference, with an estimate of 132.3 *ms* (SE = 44.8, df = 92.9, t = -2.96), with p = .01 indicating that participants performed significantly faster in Dual LC group than Dense CSC group. Similarly, when comparing performance between Dense CSC group and Single LC group, there was a significant difference, with Single LC group performing faster than Dense CSC group, with an estimated difference of 117 *ms* (SE = 42.6, df = 84.4, t = 2.76), where p = .02.

In contrast, the comparison between the dual and single contexts showed no significant difference, with an estimate of 14.7 *ms* (SE = 44.7, df = 92.4, t = -0.33), p = .94, suggesting that performance in of Dual LC group, while faster, was similar to that of Single LC group.

These results indicate that while the Dual LC group had faster performance than Dense CSC group and Single LC group, it only differed significantly from Dense CSC group, but not Single LC group.

*EM Means- Task condition*

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Pure (Colour)*** | 611 | 31.3 | 3.56 | 520 | 703 |
| ***Pure (Shape)*** | 606 | 31.4 | 3.58 | 514 | 697 |
| ***Alternate*** | 673 | 30.8 | 3.40 | 582 | 765 |
| ***Mixed*** | 665 | 30.8 | 3.37 | 573 | 757 |

*Table 4.5.50: Group-wise EM Means based on task condition of global switch cost performance in bivalent task.*

An analysis of estimated marginal means was conducted across different task conditions to assess performance outcomes *(table 4.5.50)*. Pure (Shape) task condition showed fastest performance, with an estimated mean of 606 *ms* (SE = 31.4, df = 3.58, 95% CI [514, 697]). Performance in Pure (Colour) task condition followed closely, with an estimated mean of 611 *ms* (SE = 31.3, df = 3.56, 95% CI [520, 703]). Mixed task condition came next, with an estimated mean of 665 *ms* (SE = 30.8, df = 3.37, 95% CI [573, 757]). Alternate task condition closely followed with an estimated average of 673 *ms* (SE = 30.8, df = 3.40, 95% CI [582, 765]).

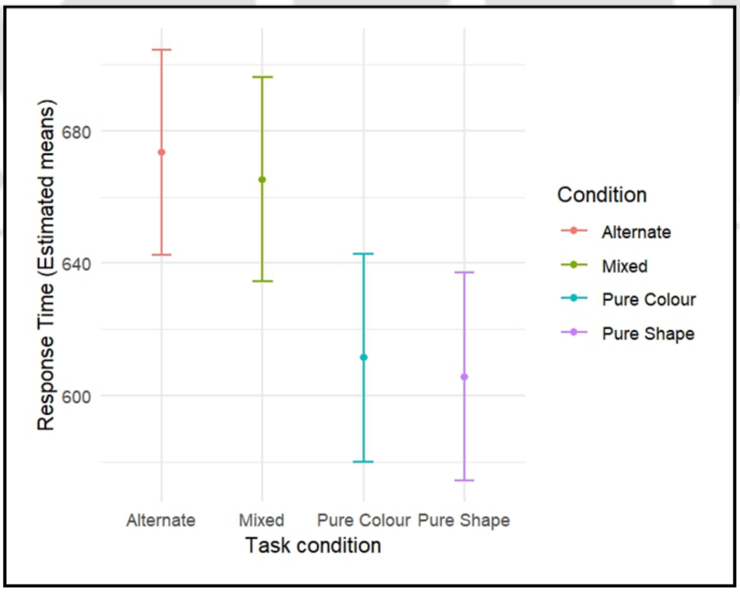


*Figure 4.5.29: Group-wise EM Means performance based on task condition of global switch cost performance in bivalent task. Performance in Pure (Shape) task condition was the fastest, closely followed by Pure (Colour) condition, then came Mixed condition, and finally Alternate task condition. Bars represent 95% confidence intervals.*

These results indicate that performance in both the Pure task conditions were closer in difference, with Pure (Shape) being faster, performance in Alternate task condition stood out with the highest mean performance, although the difference in performance between Alternate and Mixed task conditions was relatively low *(see figure 4.5.29 for graphical representation)*.

*Pairwise analysis- Task condition*

| Contrast | Estimate | SE | df | t ratio | p value |
|---|---|---|---|---|---|
| ***Pure (Colour) - Pure (Shape)*** | 5.66 | 15.7 | 912 | 0.36 | .98 |
| ***Alternate - Pure (Colour)*** | 62.08 | 12.1 | 2764 | 5.14 | < *.0001* |
| ***Alternate - Pure (Shape)*** | 67.74 | 12.0 | 2769 | 5.66 | < *.0001* |
| ***Alternate - Mixed*** | 8.15 | 10.8 | 4396 | 0.75 | .88 |
| ***Mixed - Pure (Colour)*** | 53.93 | 12.3 | 2956 | 4.39 | *.0001* |
| ***Mixed - Pure (Shape)*** | 59.59 | 12.3 | 2753 | 4.84 | < *.0001* |

*Table 4.5.51: Pair-wise analysis based on task condition of global switch cost performance in bivalent task.*

A series of pairwise comparisons were conducted to examine the differences in estimated marginal means across various conditions. When comparing performance of Pure (Colour) and Pure (Shape) task conditions, performance in Pure (Shape) was faster, however, this difference was not significant, with an estimated difference of 5.66 *ms* (SE = 15.7, df = 912, t = 0.36), where p = .98. Similarly, the difference in performance between Alternate and Mixed task conditions showed that the difference was not significant, with performance in Mixed condition faster than Alternate condition, with an estimated difference of 8.15 *ms* (SE = 10.8, df = 4396, t = 0.75), with p = .88.

On the other hand, comparing performances between Alternate task condition with Pure (Colour) showed a significant difference, Pure (Colour) condition had faster performance, with an estimated difference of 62.08 *ms* (SE = 12.1, df = 2764, t = 5.14), with $p < .0001$. Similarly, when performance in Alternate task condition was compared with that of Pure (Shape) condition, there was an estimated difference of 67.74 *ms* (SE = 12.0, df = 2769, t = 5.66), with $p < .0001$, where Pure (Shape) condition had faster performance.

Mixed task condition, when compared to Pure (Colour) condition, showed significantly slower performance, with an estimated difference of 53.93 *ms* (SE = 12.3, df = 2956, t = 4.39), with $p = .0001$. Mixed task condition was also found to be significantly slower than Pure (Shape) task condition, with an estimated difference of 59.59 *ms* (SE = 12.3, df = 2753, t = 4.84), with $p < .0001$.

These findings show that the difference in performances between the Pure conditions and Alternate and Mixed conditions were not significant. However, when comparing performances between Alternate and Pure task conditions, and Mixed and Pure task conditions, the differences were found to be significant.

*EM Means- LC * Condition*

| LC | Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Pure (Colour)*** | 560 | 40.6 | 9.80 | 469 | 651 |
| ***Single*** | ***Pure (Shape)*** | 602 | 40.5 | 9.66 | 511 | 692 |
| ***Single*** | ***Alternate*** | 619 | 40.0 | 9.37 | 529 | 709 |
| ***Single*** | ***Mixed*** | 638 | 40.2 | 9.51 | 548 | 728 |
| ***Dual*** | ***Pure (Colour)*** | 583 | 43.0 | 12.20 | 489 | 676 |
| ***Dual*** | ***Pure (Shape)*** | 520 | 43.0 | 12.19 | 426 | 613 |
| ***Dual*** | ***Alternate*** | 635 | 42.6 | 11.92 | 542 | 728 |
| ***Dual*** | ***Mixed*** | 622 | 42.4 | 11.70 | 530 | 715 |
| ***Dense*** | ***Pure (Colour)*** | 691 | 40.8 | 9.99 | 600 | 782 |
| ***Dense*** | ***Pure (Shape)*** | 696 | 40.6 | 9.75 | 605 | 787 |
| ***Dense*** | ***Alternate*** | 766 | 40.5 | 9.78 | 676 | 856 |
| ***Dense*** | ***Mixed*** | 736 | 40.0 | 9.32 | 646 | 826 |

*Table 4.5.52: Group-wise EM Means based on interaction between LC and task condition of global switch cost performance in bivalent task.*

Estimated marginal means (EM means) for assessing performance of the different language context groups in the various task conditions.

In the Pure (Colour) condition, Single LC group had the fastest performance, with a mean estimate of 560 *ms* (SE = 40.6, df = 9.80, 95% CI [469, 651]). Dual LC group followed, with an estimated mean of 583 *ms* (SE = 43.0, df = 12.20, 95% CI [489, 676]). Dense CSC group had an average performance of 691 *ms* (SE = 40.8, df = 9.99, 95% CI [600, 782]).

In Pure (Shape) condition, Dual LC group showed the lowest average mean of 520 *ms* (SE = 43.0, df = 12.19, 95% CI [426, 613]). Single LC group followed, with an estimate of 602 *ms* (SE = 40.5, df = 9.66, 95% CI [511, 692]). Dense CSC group followed last with an estimated average of 696 *ms* (SE = 40.6, df = 9.75, 95% CI [605, 787]).

Alternate task condition saw Single LC group outperform the others with an estimated average of 619 *ms* (SE = 40.0, df = 9.37, 95% CI [529, 709]). Dual LC group came next with a mean of 635 *ms* (SE = 42.6, df = 11.92, 95% CI [542, 728]). Dense CSC group had an estimated average of 766 *ms* (SE = 40.5, df = 9.78, 95% CI [676, 856]).

Performance in Mixed task condition found Dual LC group have fastest performance, with an estimated average of 622 *ms* (SE = 42.4, df = 11.70, 95% CI [530, 715]). They were followed by Single LC group, with a mean of 638 *ms* (SE = 40.2, df = 9.51, 95% CI [548, 728]). Dense CSC group showed the slowest performance, with estimated mean of 736 *ms* (SE = 40.0, df = 9.32, 95% CI [646, 826]).

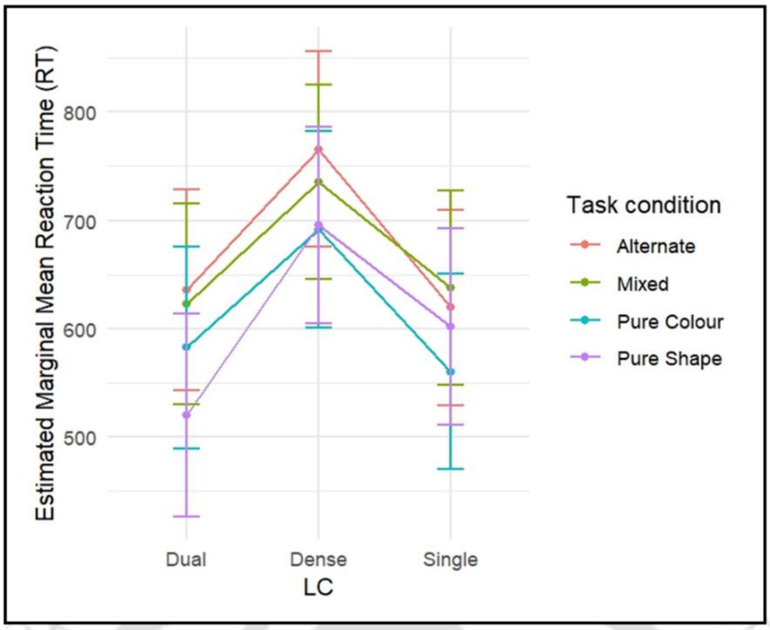


*Figure 4.5.30: Interaction of LC × Task condition of global switch cost performance in bivalent task.*

Overall, these findings suggest that Single LC group and Dual LC group were shown to outperform the others alternately in various task conditions. Dense CSC group, however, consistently had the slowest performance in all the different task conditions.

***Accuracy analysis***

*Error rate.* Error-rate analysis revealed that Dual LC group had the least errors (3.79%%), followed by Single LC group (5.82%), and then came Dense CSC group (6.30%).

*GLMM.* A generalized linear mixed model (GLMM) was conducted to examine the effects of language context (LC) and task condition on performance errors, with Subject as a random effect.

The fixed effect of language context showed that comparison among the different levels were not significant statistically. Single LC group and Dense CSC group showed lower accuracy rate than Dual LC group, and Single LC group had lower accuracy rate than Dense CSC group.

When examining task conditions, comparisons between some levels showed statistical significance, for instance, between Pure (Shape) and Mixed task conditions, there was an estimated difference of 1.14 (SE = 0.37, z = 3.07), with $p$ = .002, where accuracy of Mixed task condition was lower than Pure (Shape) condition. Pure (Colour) showed lower accuracy than Pure (Shape), with an estimated difference of 0.92 (SE = 0.46, z = -2.01), with $p$ = .04. Other comparisons showed that Pure (Colour), Pure (Shape), and Mixed task conditions showed lower accuracy rate than Alternate task condition. Mixed task condition showed lower accuracy rate than Pure (Colour).

Response time (RT) was significantly negatively correlated with error rates, with an estimate of 0.40 (SE = 0.08, z = -5.17), with $p < .001$, indicating that as reaction times increased, the likelihood of errors decreased.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -3.80 | 0.49 | -7.78 | < *.001* |
| ***LC*** | | | | |
| DLC vs. SLC | 0.65 | 0.46 | 1.43 | .15 |
| DLC vs. DCS | 0.05 | 0.50 | 0.10 | .92 |
| SLC vs. DCS | -0.60 | 0.45 | -1.34 | .18 |
| ***Task condition*** | | | | |
| Alternate vs. Pure (Colour) | 0.46 | 0.44 | 1.05 | .30 |
| Alternate vs. Pure (Shape) | -0.46 | 0.42 | -1.10 | .27 |
| Alternate vs. Mixed | 0.68 | 0.37 | 1.82 | *.07* |
| Pure (Colour) vs. Pure (Shape) | -0.92 | 0.46 | -2.01 | *.04* |
| Pure (Colour) vs. Mixed | 0.22 | 0.40 | 0.55 | .58 |
| Pure (Shape) vs. Mixed | 1.14 | 0.37 | 3.07 | *.002* |
| ***Response time*** | | | | |
| RT (scaled) | -0.40 | 0.08 | -5.17 | < *.001* |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Alternate vs. Pure (Colour) | -0.56 | 0.54 | -1.04 | .30 |
| DLC vs. DCS: Alternate vs. Pure (Colour) | 0.14 | 0.58 | 0.23 | .82 |
| SLC vs. DCS: Alternate vs. Pure (Colour) | 0.69 | 0.53 | 1.32 | .19 |
| DLC vs. SLC: Alternate vs. Pure (Shape) | 0.15 | 0.51 | 0.29 | .77 |
| DLC vs. DCS: Alternate vs. Pure (Shape) | 0.93 | 0.54 | 1.71 | *.09* |
| SLC vs. DCS: Alternate vs. Pure (Shape) | 0.79 | 0.46 | 1.71 | *.09* |
| DLC vs. SLC: Alternate vs. Mixed | -0.55 | 0.47 | -1.16 | .25 |
| DLC vs. DCS: Alternate vs. Mixed | 0.67 | 0.51 | 1.33 | .18 |
| SLC vs. DCS: Alternate vs. Mixed | 1.23 | 0.45 | 2.71 | *.007* |
| DLC vs. SLC: Pure (Colour) vs. Pure (Shape) | 0.70 | 0.53 | 1.34 | .18 |
| DLC vs. DCS: Pure (Colour) vs. Pure (Shape) | 0.80 | 0.54 | 1.48 | .14 |
| SLC vs. DCS: Pure (Colour) vs. Pure (Shape) | 0.09 | 0.48 | 0.19 | .85 |
| DLC vs. SLC: Pure (Colour) vs. Mixed | 0.005 | 0.50 | 0.01 | .99 |
| DLC vs. DCS: Pure (Colour) vs. Mixed | 0.54 | 0.50 | 1.07 | .28 |
| SLC vs. DCS: Pure (Colour) vs. Mixed | 0.53 | 0.47 | 1.13 | .26 |
| DLC vs. SLC: Pure (Shape) vs. Mixed | -0.70 | 0.47 | -1.50 | .13 |
| DLC vs. DCS: Pure (Shape) vs. Mixed | -0.26 | 0.46 | -0.57 | .57 |
| SLC vs. DCS: Pure (Shape) vs. Mixed | 0.44 | 0.40 | 1.10 | .27 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.69 | 0.83 |
| Task | (Intercept) | 0.22 | 0.47 |

*Table 4.5.53: GLMM results of error analysis of global switch cost performance in bivalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

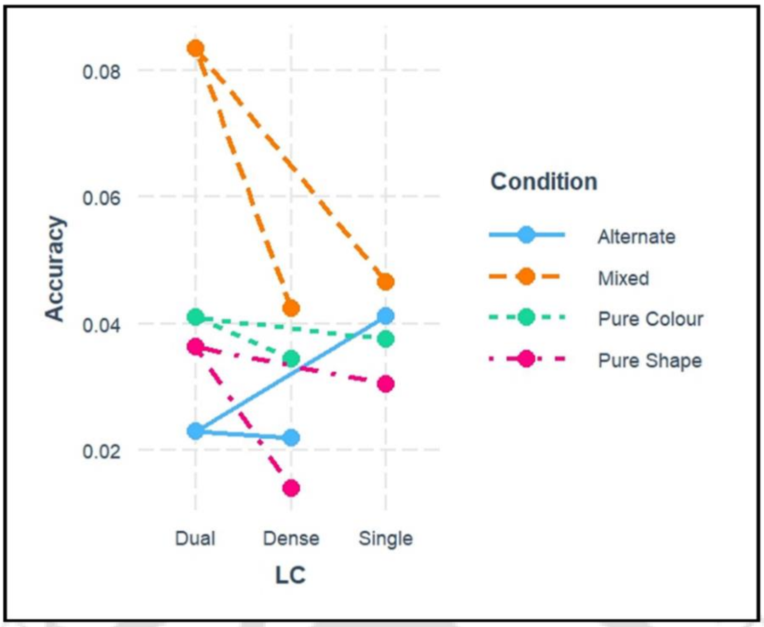


*Figure 4.5.31: Graph showing error analysis of global switch cost performance in bivalent task. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

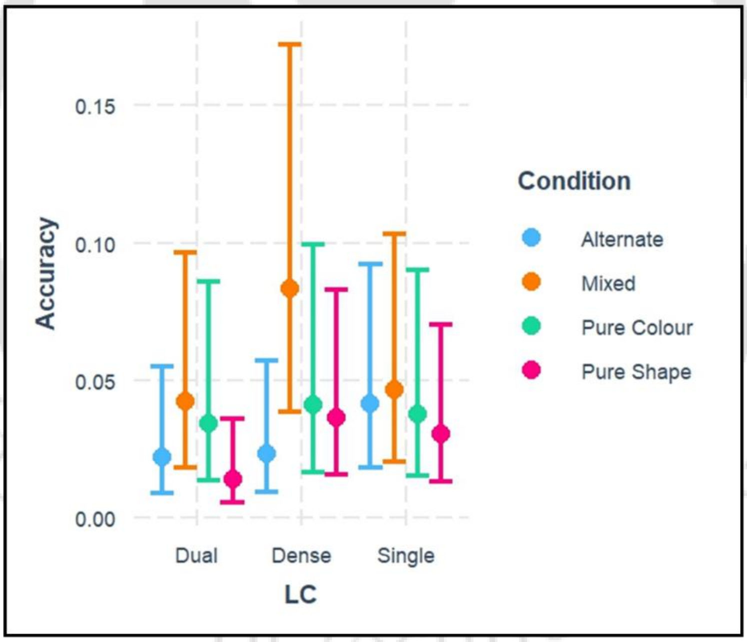


*Figure 4.5.32: Error analysis of each LC group of global switch cost performance in bivalent task. Each coloured bar represents a different task condition.*

The interaction effects involving LC and condition were generally non-significant, although the interaction between Dual LC and Dense CSC groups, when comparing their performance between Alternate and Pure (Shape) condition approached significance, with a significance of 0.93 (SE = 0.54, z = 1.71), $p = .09$.

Overall, the findings suggest that while there were trends in the data, many comparisons did not reach statistical significance, indicating the complexity of the relationships between language context, task condition, and error rates performance in global switch cost *(see figure 4.5.31, 4.5.32 for graphical representations)*.

### *Post-error analysis*

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 663.65 | 35.09 | 9.81 | 18.91 | < *.001* |
| Post error | 44.37 | 57.36 | 112.02 | 0.77 | .44 |
| ***LC*** | | | | | |
| DLC vs. SLC | 24.94 | 40.03 | 57.76 | 0.62 | .54 |
| DLC vs. DCS | 135.86 | 40.06 | 57.91 | 3.39 | *.001* |
| SLC vs. DCS | 110.92 | 39.07 | 58.07 | 2.84 | *.006* |
| ***Task condition*** | | | | | |
| Alternate vs. Pure (Colour) | -68.45 | 11.99 | 2088.28 | -5.71 | < *.001* |
| Alternate vs. Pure (Shape) | -74.20 | 11.91 | 2155.37 | -6.23 | < *.001* |
| Alternate vs. Mixed | -11.27 | 11.08 | 4357.95 | -1.02 | .31 |
| Pure (Colour) vs. Pure (Shape) | -5.76 | 14.97 | 545.84 | -0.39 | .70 |
| Pure (Colour) vs. Mixed | 57.17 | 12.34 | 2098.86 | 4.63 | < *.001* |
| Pure (Shape) vs. Mixed | 62.93 | 12.15 | 2367.37 | 5.18 | < *.001* |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | -19.26 | 61.42 | 43.26 | -0.31 | .76 |
| Post error: DLC vs. DCS | -52.76 | 61.63 | 46.99 | -0.86 | .39 |
| Post error: SLC vs. DCS | -33.49 | 57.82 | 39.84 | -0.58 | .57 |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Alternate vs. Pure (Colour) | 117.35 | 58.47 | 1703.48 | 2.01 | *.04* |
| Post error: Alternate vs. Pure (Shape) | 179.75 | 51.88 | 1599.82 | 3.47 | *.0005* |
| Post error: Alternate vs. Mixed | -24.48 | 49.37 | 2028.34 | -0.50 | .62 |
| Post error: Pure (Colour) vs. Pure (Shape) | 62.40 | 54.88 | 1887.11 | 1.14 | .26 |
| Post error: Pure (Colour) vs. Mixed | -141.83 | 52.39 | 2293.65 | -2.71 | *.007* |
| Post error: Pure (Shape) vs. Mixed | -204.23 | 44.87 | 1964.34 | -4.55 | < *.001* |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Corr** |
| Subject | (Intercept) | 15089.3 | 122.84 | |
| | Post Error | 13283.1 | 115.25 | -0.27 |
| Task | (Intercept) | 696.2 | 26.38 | |
| Residual | | 63047.3 | 251.09 | |

*Table 4.5.54: LMM results of post-error performance of global switch cost performance in bivalent task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed model (LMM) was conducted to investigate the effects of post-error trials and LC on performance, with Subject as a random effect. For subject, the variance (Var = 15,089.3, SD = 122.84) indicates substantial differences in average response times among participants, while the random slope for post-error trials (Var = 13,283.1, SD = 115.25) shows variability in how participants adjust their response times following errors. The correlation between the random intercept and slope of post-error was negative (corr = −0.27), suggesting that participants with greater average RTs exhibit smaller post-error adjustments, whereas those with lower average response times show larger adjustments. The residual variance (Var = 63,047.3, SD = 251.09) captures unexplained variability in response times not accounted for by the fixed or random effects.

The effect of post-error trials was not significant, with an estimate of 44.37 (SE = 57.36, t = 0.77), $p$ = .44, suggesting that prior errors did not significantly affect subsequent performance in this analysis.

The interaction between post-error performance and LC groups showed no statistical significance. Dual LC group had faster post-error performance than Single LC group and Dense CSC groups. Dense CSC group, in turn, had slower performance than Single LC group.

The task condition and post-error performance interaction showed significance for comparison between some levels. Alternate task condition showed slower performance than Pure (Colour) with an estimated difference of 117.35 *ms* (SE = 58.47, t = 2.01), with $p$ = .04; as well as slower than Pure (Shape) had an estimated difference of 179.75 *ms* (SE = 51.88, t = 3.47), with $p$ = .0005. Mixed task condition also showed slower post-error performance compared to Pure (Shape), with an estimated difference of 204.23 *ms* (SE = 44.87, t = -4.55), with $p$ = < .001; as well as Pure (Colour), with an estimated difference 141.83 *ms* (SE = 52.83, t = -2.71), with $p$ = .007. Pure (Colour) showed slower performance than Pure (Shape) but this difference was not statistically significant.

Overall, these results suggest that task condition might significantly impact post-error performance, however, LC group did not affect the performance.

## 4.6 Discussion

The aim of this set of experiments was to examine the performance of bilinguals in general executive function tasks to see if there were any spillover effects that may come from being bilingual, into task switching performance. To this end, univalent and bivalent switching tasks were used to measure the general executive functions of the bilingual participants and examine whether their contextual language usage determined the performance.

Based on their language usage in various contexts the participants are divided into three categories: Single-language context, Dual-language context and Dense code-switching context. As per the Adaptive Control Hypothesis, the assumption was that, given the cognitive mechanisms in place during Dual-language interactional context, the participants engaged in this context would outperform the Single-language and Dense code-switching context participants in non-linguistic executive control functions as well.

The results showed that Dual LC group, for the most part showed fastest performance in most parameters of the tasks. With the exception of local switch cost performance in bivalent switching task, where Single LC showed lowest mean RT, Dual language context group outperformed the other groups in speed-related performance. The above results showed how this research aligns with the notion put forward by the Adaptive Control Hypothesis, which posits that the control mechanism exerted in Dual-language context would influence the performance in various non-linguistic scenarios. The constant awareness of one's environment, monitoring of the activated languages and switching between languages when required mirrors the mechanisms involved in switching between tasks. In task switching the participants has to be aware of cue activating the task to be performed, remember the tasks to be performed and respond accordingly.

The Single-language context has separate language for separate environments, which aids in categorising the different tasks and their respective responses, thus also explaining the least errors the Single LC group had among the three groups in all variables of the univalent task. The distinct environment for each language, with no language switching taking place is mirrored in the univalent task setting, where each task performed is distinct, with no overlap in stimulus presented or their corresponding response keys. On the other hand, in a bivalent task, different tasks are performed on the same set of stimuli, which seem to mimic the dual-language context scenario, where the environment is the same, and depending on the cues the participant gets from their surroundings, the language to be spoken is chosen. This would explain the accuracy rate of the Dual LC group compared to the other groups, as well as them showing fastest performance in all variables of the bivalent task.

Thus, the spillover effect of the interactional behaviour of the bilinguals is visible not just in the speed or accuracy of their performances, but also in the conditions that mimic their interactional contexts. This shows a positive feedback towards the much-debated presence of the bilingual advantage.

## 4.7 Chapter summary

This chapter examined flexibility and switching performance among bilingual young adults, focusing on how contextual language usage influences executive control functioning. This was examined in two experiments using three switching tasks: bivalent magnitude/parity numbers task for Experiment 1, and univalent number/letter task and bivalent shape/colour task for Experiment 2.

For each task, the chapter details participants' description, experimental design, methodology and procedures, followed by the statistical analysis and discussion of results. The participants were categorized based on their language switching behaviour. Results revealed that bilinguals that were engaged in Dual language context showed efficient switching performance, across most task conditions. This suggests that bilingual experiences may contribute to the fine-tuning of cognitive processes that underly switching mechanisms.

The following chapter shifts focus to the working memory performance of young adult bilinguals, and how their bilingual experience shapes said performance, as assessed through the *N*-Back task.

# 5 Bilingualism and Working memory

## 5.1 Introduction

Working memory is yet another core component of the executive control mechanism in humans. The working memory is responsible for holding information, constantly updating it with changes in the environment, and working on the updated information (Diamond, 2013).

Bilingual individuals continuously engage their working memory as they switch between languages, monitor for interference from other languages, and then select the appropriate language in a specific context. This constant cognitive exercise requires active maintenance and manipulation of linguistic information, which places significant demands on the working memory capacity.

Over the years, a number of studies have investigated the role of working memory in bilingual language processing (Antón et al., 2019; Jiao et al., 2019; Morrison et al., 2019; Nour et al., 2020). Several studies found an advantage of being bilingual over monolinguals in working memory tasks. Morrison et al. (2019) for instance, recorded the brain activity, or event-related potentials (or ERPs) of monolinguals and bilinguals, using Electroencephalography (EEG), while they performed the *N*-Back task. They specifically wanted to look at specific waveforms, such as the P300, which is involved in cognitive processes such as attention, memory processing, etc. They hypothesized that while both, monolinguals and bilinguals will show reduced P300 amplitude due to increasing working memory load, the bilinguals were expected to have larger P300 amplitude than monolinguals. Results found that while monolinguals and bilinguals had similar performance in accuracy and reaction time, the monolinguals had smaller P300 amplitudes, demonstrating a lesser cognitive resource allocation than bilinguals.

## 5.2 Chapter overview

This chapter explores the association between working memory performance and contextual language usage patterns in bilingual young adults. Through the premise of the ACH, this chapter investigates whether habitual language switching modulates working memory abilities through their performance in the *N*-Back task which is commonly used for this paradigm. The participants are categorised based on their language switching habits and their performance in the task are then analysed and compared. The findings are then interpreted, arguing for the cognitive implications of contextual language usage of bilinguals.

## 5.3 Objective and Hypothesis

The objective of this chapter is to examine the working memory performance of young adult bilinguals and investigate a relationship between their interactional language switching practices and working memory capacity. The hypothesis tested was that the more complex the language switching context, better the working memory performance.

## 5.4 *N*-Back task

The N-Back task is often used for examination and study of the working memory (Morrison et al., 2019). The purpose of the experiment is to determine if the stimulus present on the screen matches the stimulus presented *n* items ago. The *n* changes depending upon the condition. For this particular experiment, there were 3 *N*-Back conditions: 1-Back, 2-Back, and 3-Back.

### 5.4.1 Participants

A total of 61 participants took part in the experiment, the same participants as in the previous univalent and bivalent switching experiments *(see Chapter 4)*.

### 5.4.2 Design and tools

The experiment involved single digit numbers from 1 to 9 being displayed on the screen one after the other. Depending upon the condition, 1-back, 2-back, or 3-back, the participants had to determine if the number was a 'target' or a 'non-target' number. For 1-back condition, a number was a 'target' number if it was the same as the previous number, otherwise it was a 'non-target' number. For 2-back condition, a number was a 'target' number if the number on the screen was the same as the number presented 2 digits before. In 3-back condition, a number was considered a 'target' number if it matched the number that appeared 3 numbers back, otherwise it was a 'non-target' number. The fixation cross (+) as well as the digits displayed were yellow text on a navy-blue background. The response keys used were 'B' and 'V'. The response to the keys were counterbalanced across participants. There was a brief practice session preceding the main session. Figure 5.4.1. depicts a schematic diagram of the task.

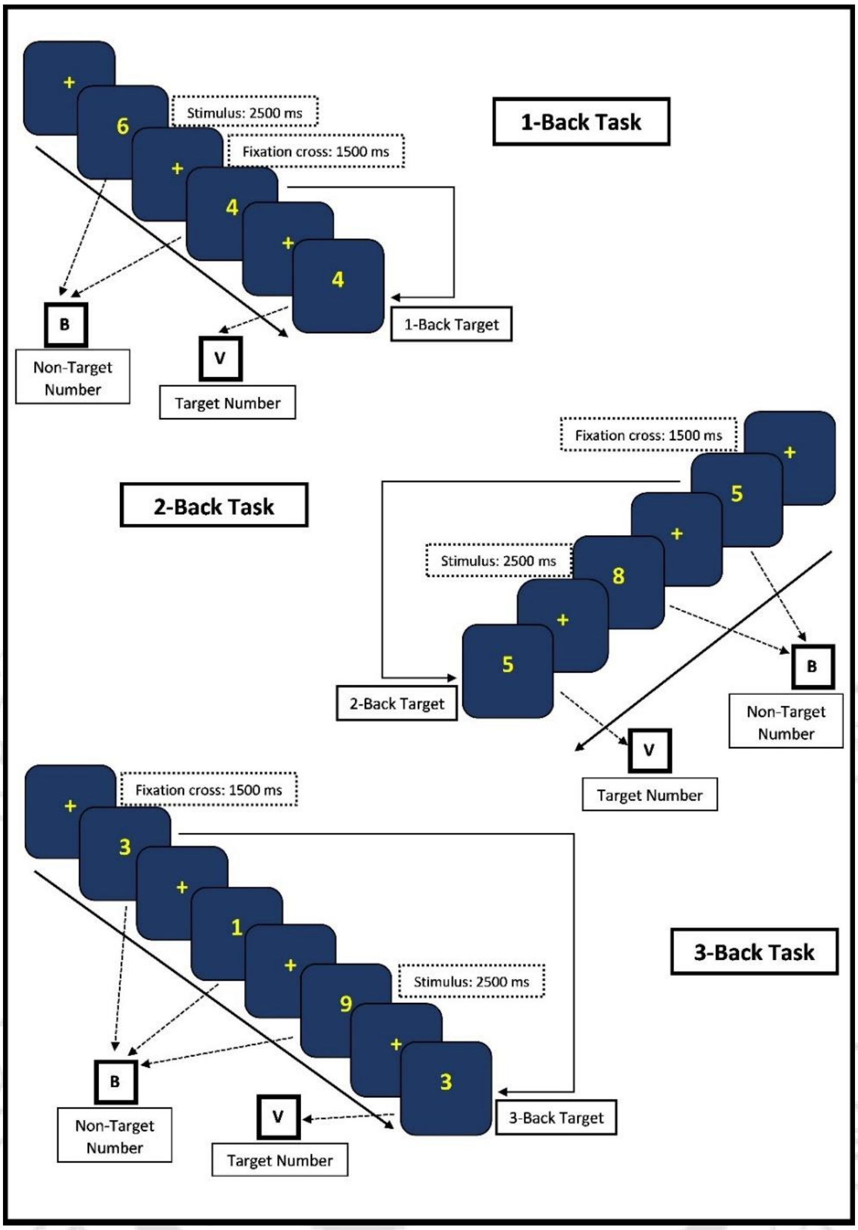


*Figure 5.4.1: Schematic diagram of N-Back task performed.*

### 5.4.3 Procedure

After a brief explanation and set of instruction on how to perform the task, the participants were made to practice a little after which they performed the main session. The practice session had 60 trials in total. The participants had to perform 30 trials each of 1-back and 2-back conditions. After the instructions, the participants first had to perform the 1-back task for 30 trials and then 30 trials for the 2-back task. The fixation cross appeared for 1500 *ms*, followed by a single digit number. The participants had to decide if the number on the screen was a target or a non-target number; in other words, the participant had to press yes or no. There was no time constraint for the practice session. The feedback that followed for 1500 *ms* only recorded if the response was correct or incorrect. After the practice session, the participants moved on to the main session. The main session consisted of 120 trials. There were 3 conditions, 40 trials for each of the three conditions. Along with the 1-back and the 2-back, the participants also performed the 3-back condition. After the fixation cross appeared for 1500 *ms*, the stimulus screen appeared showing just a single digit for 2500 *ms*. Depending upon the condition, the participant had to decide if the number present on the screen was a target or a non-target.

### 5.4.4 Results

#### 5.4.4.1 Questionnaire analysis

The questionnaire analysis is the same as in Chapter 4.

#### 5.4.4.2 Task analysis

***RT analysis***

*Linear mixed-model analysis*

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 847.80 | 95.22 | 2.53 | 8.90 | *.006* |
| ***LC*** | | | | | |
| DLC vs. DCS | 3.89 | 45.01 | 67.46 | 0.09 | .93 |
| DLC vs. SLC | 26.70 | 44.99 | 67.42 | 0.59 | .55 |
| SLC vs. DCS | -22.81 | 43.86 | 67.39 | -0.52 | .60 |
| ***Task condition*** | | | | | |
| 1-Back vs. 2-Back | 38.29 | 15.20 | 6859.87 | 2.52 | *.01* |
| 1-Back vs. 3-Back | 143.07 | 15.41 | 6857.65 | 9.29 | *< .001* |
| 2-Back vs. 3-Back | 104.78 | 15.40 | 6960.41 | 6.81 | *< .001* |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -66.67 | 22.10 | 7042.26 | -3.02 | *.003* |
| ***LC x Condition interaction*** | | | | | |
| DLC vs. SLC: 1-Back vs. 2-Back | 84.27 | 21.00 | 7014.85 | 4.01 | *< .001* |
| DLC vs. DCS: 1-Back vs. 2-Back | 93.53 | 20.93 | 7014.54 | 4.47 | *< .001* |
| SLC vs. DCS: 1-Back vs. 2-Back | 9.26 | 20.50 | 7014.86 | 0.45 | .65 |
| DLC vs. SLC: 1-Back vs. 3-Back | 19.26 | 21.29 | 7015.59 | 0.91 | .37 |
| DLC vs. DCS: 1-Back vs. 3-Back | 36.42 | 21.17 | 7015.25 | 1.72 | *.09* |
| SLC vs. DCS: 1-Back vs. 3-Back | 17.17 | 20.67 | 7015.28 | 0.83 | .41 |
| DLC vs. SLC: 2-Back vs. 3-Back | -65.02 | 21.28 | 7015.31 | -3.06 | *.002* |
| DLC vs. DCS: 2-Back vs. 3-Back | -57.10 | 21.19 | 7015.40 | -2.70 | *.007* |
| SLC vs. DCS: 2-Back vs. 3-Back | 7.91 | 20.71 | 7015.15 | 0.38 | .70 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | -1.80 | 30.62 | 7037.27 | -0.06 | .95 |
| DLC vs. DCS: Correct vs. Error | -22.60 | 32.10 | 7039.80 | -0.70 | .48 |
| SLC vs. DCS: Correct vs. Error | -20.79 | 31.94 | 7041.38 | -0.65 | .52 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Group** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 17992.67 | 134.14 |
| Display | (Intercept) | 21.18 | 4.60 |
| Trial Type | (Intercept) | 23809.67 | 154.30 |
| Residual | | 85579.63 | 292.54 |

*Table 5.4.1: LMM results of RT analysis of N-Back task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed model analysis was conducted to investigate the effects of language context (LC), task condition, and accuracy on the participants' RT.

The random effects analysis revealed substantial variability between participants (Variance = 17992.67, SD = 134.14) and across trial types (Variance = 23809.67, SD = 154.30). There was also residual variance (Variance = 85579.63, SD = 292.54), indicating variability that was not accounted for by the fixed effects.

In terms of language context groups, no significant differences were observed between the various groups, thus indicating that the differences between these groups is not statistically significant. Results showed that Dual LC group had a faster performance than Single LC group and Dense CSC group. Dense CSC group were faster than Single LC group.

The task condition results indicated significant differences among all three comparisons. Specifically, the 1-Back condition had significantly shorter RTs than the 2-Back condition, with an estimated difference of 38.29 *ms* (SE=15.20, t = 2.52), $p = .01$. The difference between the 1-Back and 3-Back conditions was even more pronounced, with an estimated difference of 143.07 *ms* (SE=15.41, t = 9.29), where $p < .001$. 2-Back condition also showed significantly faster RTs compared to the 3-Back condition, having an estimated difference of 104.78 *ms* (SE=15.40, t = 6.81), with $p < .001$.

Accuracy also had a significant effect on the RT, with correct responses being slower than errors, with an estimated difference of 66.67 *ms* (SE=22.10, t = −3.02), $p = .003$.

The interaction between LC and task condition revealed several significant contrasts. For the 1-Back vs. 2-Back comparison, the Dual LC group vs. Single LC group interaction was significant, with an estimate of 84.27 *ms* (SE=21.00, t = 4.01), with $p < .001$. Similarly, the Dual LC group vs. Dense CSC group interaction showed an estimated difference of 93.53 *ms* (SE=20.93, t = 4.47), where $p < .001$. The Single LC group vs. Dense CSC group interaction in this comparison was not significant, having an estimate of 9.26 *ms* (SE=20.50, t = 0.45), with $p = .65$.

In the 1-Back vs. 3-Back comparison, no significant interactions were observed among the LC conditions, except in Dual LC group vs. Dense CSC group, with an estimated difference of 36.42 *ms* (SE = 21.17, t = 1.72), with p = .09, reaching near significance. In the 2-Back vs. 3-Back comparison, significant interactions emerged between Dual LC group vs. Single LC group, with an estimated difference of 65.02 *ms* (SE=21.28, t = −3.06), with $p = .002$. Between Dual LC group vs. Dense CSC group there was an estimated difference of 57.10 *ms* (SE=21.19, t = −2.70), $p = .007$, suggesting differential effects of language context on task performance between these conditions. The interaction between LC and accuracy did not produce significant results in any comparison.

Overall, the results suggest that task complexity significantly affects RTs, with more complex tasks (e.g., 3-Back) leading to longer response times. The effects of language context were not significant in isolation but showed notable interactions with task conditions, indicating that language context might modulate performance differently depending on task demands.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 154152 | 77076 | 2 | 69.3 | 0.90 | .41 |
| ***Task condition*** | 30580522 | 15290261 | 2 | 5634.9 | 178.67 | < *.001* |
| ***Accuracy*** | 2661692 | 2661692 | 1 | 7038.3 | 31.10 | < *.001* |
| ***LC: Task condition*** | 2173542 | 543385 | 4 | 7015.1 | 6.35 | < *.001* |
| ***LC: Accuracy*** | 51197 | 25599 | 2 | 7039.0 | 0.30 | .74 |

*Table 5.4.2: Type III Analysis of Variance Table with Satterthwaite's method for N-Back task performance.*

A Type III ANOVA was conducted to assess the effects of language context (LC), task condition, and accuracy, along with their interactions, on reaction times (RT). The results revealed no significant main effect of language context, F(2,69.3) = 0.90, with $p$ = .41, indicating that the different LC groups did not significantly influence RTs overall.

However, task condition showed a highly significant main effect, F(2,5634.9) = 178.67, with $p$ < .001, suggesting that RTs varied substantially across different task conditions. Additionally, accuracy also had a significant main effect, F(1,7038.3) = 31.10, with $p$ < .001, indicating that correct responses differed significantly from error responses in terms of RTs.

The interaction between language context and task condition was also significant, F(4, 7015.1) = 6.35, $p$ < .001, suggesting that the relationship between task condition and RTs varied depending on the language context. In contrast, the interaction between language context and accuracy was not significant, F(2,7039.0) = 0.30, with $p$ = .74, indicating that the effect of accuracy on RTs did not differ across language contexts.

Overall, these results highlight the substantial influence of task condition and accuracy on RTs and suggest that language context may modulates the effect of task condition but not accuracy.

***Post-HOC analysis***

*EM Means- Language context*

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 935 | 94.6 | 2.50 | 597 | 1273 |
| ***Dual*** | 875 | 95.1 | 2.55 | 540 | 1210 |
| ***Dense*** | 911 | 94.7 | 2.51 | 573 | 1248 |

*Table 5.4.3: Group-wise EM Means based on Language Context in N-Back task performance.*

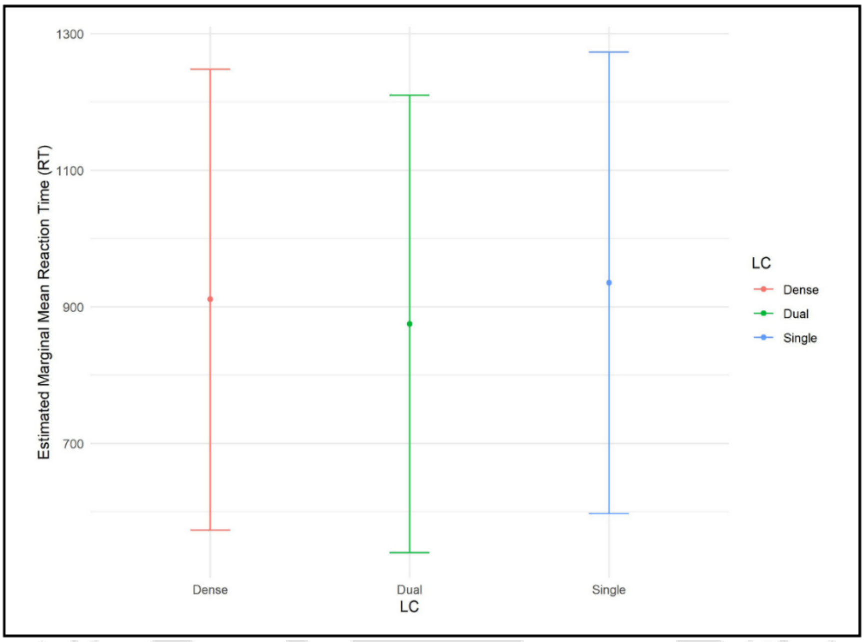


*Figure 5.4.2: Group-wise EM Means performance based on Language Context in N-Back task. Dual LC group shows the least EM means, followed by Dense CSC group, which is closely followed by Single LC group. Bars represent 95% confidence intervals*

EM means analysis was conducted to further examine the effect of language context on reaction times. The results revealed that participants in Dual LC group showed the fastest performance, with an estimated mean of 875 *ms* (SE = 95.1, df = 2.55, 95% CI [540, 1210]). They were followed by Dense CSC group, with an average estimate of 911 *ms* (SE = 94.7, df = 2.51, 95% CI [573, 1248]). Finally came the Single LC group, with an estimated average of 935 *ms* (SE = 94.6, df = 2.50, 95% CI [597, 1273]). Although there were differences in the estimated means across conditions, the overlapping confidence intervals suggest that these differences may not be statistically significant. This pattern aligns with the non-significant main effect of language context observed in the ANOVA analysis, indicating that RTs did not vary meaningfully between Single, Dual, and Dense language contexts when considering the overall variability in the data.

*Pairwise analysis- Language context*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -35.9 | 45.3 | 69.5 | -0.79 | .71 |
| ***Dense - Single*** | -24.4 | 44.3 | 70.3 | -0.55 | .85 |
| ***Dual - Single*** | -60.3 | 45.1 | 68.0 | -1.34 | .38 |

*Table 5.4.4: Pair-wise analysis based on Language context in N-Back task performance.*

A pairwise comparison analysis was conducted to evaluate the differences in reaction times (RT) across the three LC groups. The results indicated no significant differences between any of the language context pairs. Specifically, the comparison between the Dual and Dense contexts yielded an estimated difference of 35.9 *ms* (SE = 45.3, df = 70.3, t = -0.79), with $p = .71$, indicating that Dual LC group was faster than Dense CSC group, but not significantly so. Similarly, Dense CSC group and Single LC groups did not show a significant difference in RTs, with an estimated difference of 24.4 *ms* (SE = 44.3, df = 70.3, t = -0.55), with *p* = .85, with Dense CSC group being faster than Single LC group. Lastly, the comparison between the Dual and Single contexts also revealed no significant difference, with an estimated difference of 60.3 *ms* (SE = 45.1, df = 68.0, t = -1.34), with *p* = .38, indicating that while Dual LC group was faster than Single LC group, but not significantly.

Overall, these results indicate that LC did not significantly influence reaction times, suggesting that the task performance was stable across different contextual conditions.

*EM Means- Task condition*

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***1-Back*** | 821 | 91.4 | 2.18 | 457 | 1185 |
| ***2-Back*** | 918 | 91.3 | 2.17 | 553 | 1283 |
| ***3-Back*** | 982 | 91.3 | 2.17 | 617 | 1347 |

*Table 5.4.5: Group-wise EM Means based on task condition in N-Back task.*

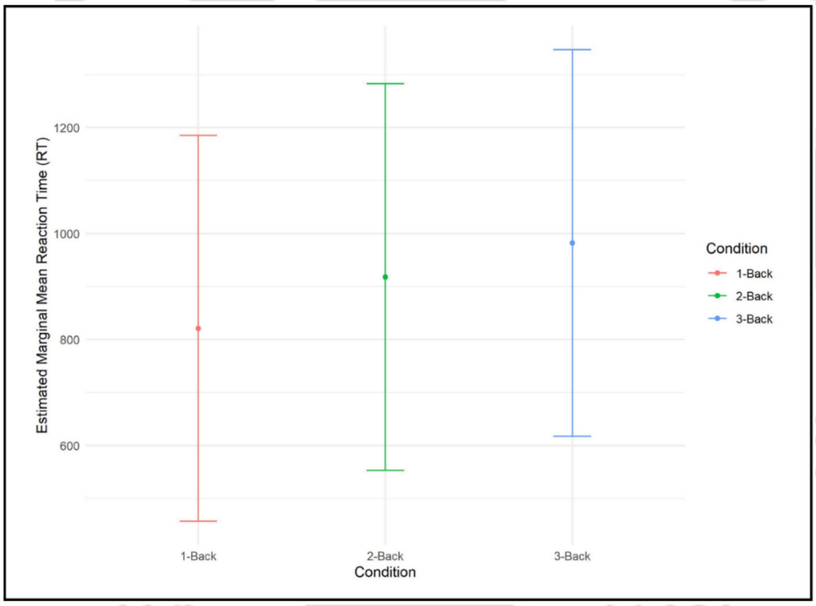


*Figure 5.4.3: Group-wise EM Means performance based on task condition in N-Back task performance. Performance in 1-Back task condition was the fastest, followed by 2-Back condition, finally followed by 3-Back task. Bars represent 95% confidence intervals.*

An estimated marginal means (EM means) analysis was conducted to examine the effect of task condition on reaction times (RT). The results indicated that participants in the 1-Back condition exhibited the fastest RTs, with an estimated mean of 821 *ms* (SE = 91.4, df = 2.18, 95% CI [457, 1185]). In the 2-Back condition, the estimated mean RT was higher at 918 *ms* (SE = 91.3, df = 2.17, 95% CI [553, 1283]). The slowest RTs were observed in the 3-Back condition, where the estimated mean was 982 *ms* (SE = 91.3, df = 2.17, 95% CI [617, 1347]).

These findings suggest that task complexity significantly influenced RTs, with performance slowing as task demands increased from the 1-Back to the 3-Back condition. The non-overlapping trends in confidence intervals between 1-Back and 3-Back conditions further support this interpretation, indicating that the differences in mean RTs across task conditions were meaningful and consistent with the overall significant main effect of task condition observed in the ANOVA.

*Pairwise analysis- Task condition*

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***1-Back – 2-Back*** | -97.6 | 8.62 | 5375 | -11.31 | < *.0001* |
| ***1-Back – 3-Back*** | -161.6 | 8.66 | 5346 | -18.66 | < *.0001* |
| ***2-Back – 3-Back*** | -64.1 | 8.67 | 6174 | -7.39 | < *.0001* |

*Table 5.4.6: Pair-wise analysis based on task condition in N-Back task performance.*

A pairwise comparison analysis was conducted to examine differences in reaction times (RT) between task conditions. The results revealed significant differences across all task pairs. The response times in the 1-Back condition were significantly faster than those in the 2-Back condition, with an estimated difference of 97.6 *ms* (SE = 8.62, df = 5375, t = -11.31), with $p < .0001$, where performance in 1-Back condition was faster. Between 1-Back and 3-Back conditions, there was an estimated difference of -161.6 *ms* (SE = 8.66, df = 5346, t = -18.66), with $p < .0001$, demonstrating that participants were substantially faster in the 1-Back task compared to the 3-Back task, reflecting the increased cognitive demands of the latter. Finally, the comparison between the 2-Back and 3-Back conditions also revealed a significant difference, where performance in 2-Back condition was faster, with an estimated difference of 64.1 *ms* (SE = 8.67, df = 6174, t = -7.39), with $p < .0001$.

Overall, these results underscore a clear and consistent effect of task complexity on performance, with RTs increasing progressively from the 1-Back to the 3-Back condition. Each incremental increase in task difficulty led to significantly slower responses, reflecting the heightened cognitive demands associated with more complex task.

*EM Means- LC x Task condition*

| LC | Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***1-Back*** | 840 | 95.1 | 2.55 | 505 | 1175 |
| ***Single*** | ***2-Back*** | 963 | 95.0 | 2.54 | 627 | 1299 |
| ***Single*** | ***3-Back*** | 1003 | 94.9 | 2.53 | 666 | 1339 |
| ***Dual*** | ***1-Back*** | 814 | 95.6 | 2.61 | 483 | 1146 |
| ***Dual*** | ***2-Back*** | 853 | 95.5 | 2.60 | 520 | 1185 |
| ***Dual*** | ***3-Back*** | 958 | 95.4 | 2.58 | 624 | 1291 |
| ***Dense*** | ***1-Back*** | 807 | 95.2 | 2.56 | 472 | 1142 |
| ***Dense*** | ***2-Back*** | 939 | 95.1 | 2.55 | 604 | 1274 |
| ***Dense*** | ***3-Back*** | 987 | 95.1 | 2.55 | 651 | 1322 |

*Table 5.4.7: Group-wise EM Means based on interaction between LC and task condition in N-Back task performance.*

An estimated marginal means (EM means) analysis was conducted to explore the interaction between language context (LC) and task condition on reaction times (RT).

In 1-Back condition, Dense CSC group showed the fastest performance with an estimated average of 807 *ms* (SE = 95.2, df = 2.56, 95% CI [472, 1142]). They were followed by Dual LC group, with an average estimate of 814 *ms* (SE = 95.6, df = 2.61, 95% CI [483, 1146]). Finally, Single LC group showed an estimate of 840 *ms* (SE = 95.1, df = 2.55, 95% CI [505, 1175]).

In 2-Back condition, Dual LC group had the fastest performance, having an estimated mean of 853 *ms* (SE = 95.5, df = 2.60, 95% CI [520, 1185]). Dense CSC group came next, with an average of 939 *ms* (SE = 95.1, df = 2.55, 95% CI [604, 1274]). Single LC group showed an estimated average of 963 *ms* (SE = 95.0, df = 2.54, 95% CI [627, 1299]).

In 3-Back condition, Dual LC group had the least average, with an estimate of 958 *ms* (SE = 95.4, df = 2.58, 95% CI [624, 1291]). Dense CSC group had an estimated mean of 987 *ms* (SE = 95.1, df = 2.55, 95% CI [651, 1322]). Single LC group had the greatest mean, with an estimate of 1003 *ms* (SE = 94.9, df = 2.53, 95% CI [666, 1339]).

Overall, these findings indicate a consistent pattern across all language contexts, where RTs increased with task complexity. With the exception of 1-Back task, Dual LC group consistently showed the fastest performance in all the task conditions, and Single LC group showed the slowest performance in all the task conditions.

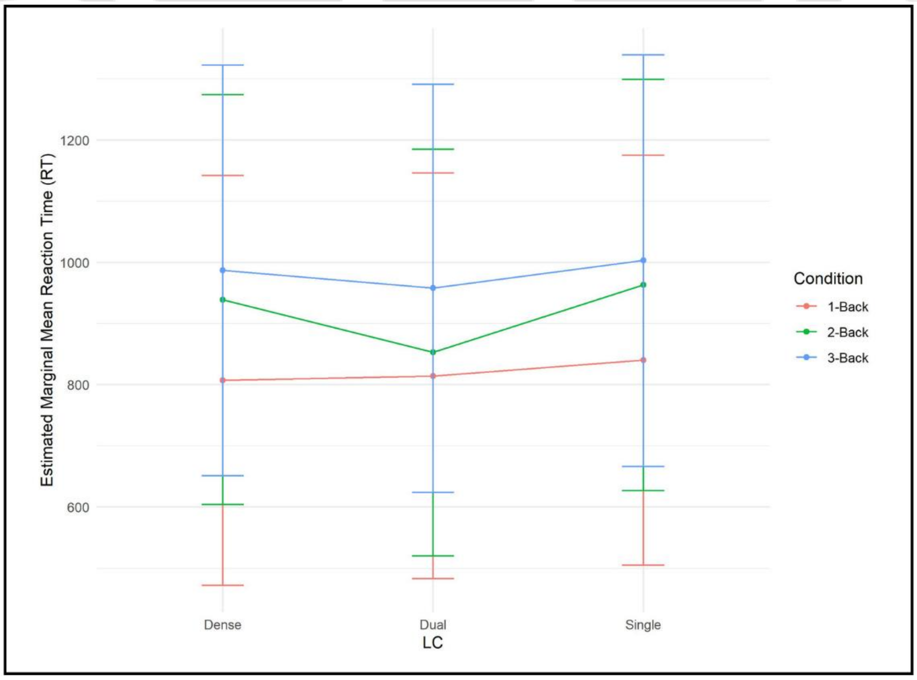


*Figure 5.4.4: Interaction of LC x Task condition in N-Back task performance.*

### ***Accuracy analysis***

*Error analysis*

*Error-rate.* Error-rate analysis revealed that Dense CSC group had the least errors (7.15%), followed by Single LC group (8.76%), and then came Dual LC group (9.57%).

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -2.31 | 0.76 | -3.04 | *.002* |
| ***LC*** | | | | |
| DLC vs. DCS | -0.13 | 0.34 | -0.38 | .70 |
| DLC vs. SLC | -0.34 | 0.35 | -0.96 | .34 |
| SLC vs. DCS | 0.20 | 0.35 | 0.59 | .56 |
| ***Task condition*** | | | | |
| 1-Back vs. 2-Back | -0.09 | 0.23 | -0.41 | .68 |
| 1-Back vs. 3-Back | 1.35 | 0.20 | 6.86 | < *.001* |
| 2-Back vs. 3-Back | 1.44 | 0.20 | 7.35 | < *.001* |
| ***Response time*** | | | | |
| RT (scaled) | -0.25 | 0.05 | -5.16 | < *.001* |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: 1-Back vs. 2-Back | 0.86 | 0.32 | 2.68 | *.007* |
| DLC vs. DCS: 1-Back vs. 2-Back | 0.02 | 0.32 | 0.07 | .95 |
| SLC vs. DCS: 1-Back vs. 2-Back | -0.84 | 0.32 | -2.62 | .009 |
| DLC vs. SLC: 1-Back vs. 3-Back | 0.19 | 0.29 | 0.68 | .50 |
| DLC vs. DCS: 1-Back vs. 3-Back | -0.58 | 0.28 | -2.06 | *.04* |
| SLC vs. DCS: 1-Back vs. 3-Back | -0.77 | 0.29 | -2.64 | *.008* |
| DLC vs. SLC: 2-Back vs. 3-Back | -0.66 | 0.26 | -2.53 | *.01* |
| DLC vs. DCS: 2-Back vs. 3-Back | -0.60 | 0.28 | -2.12 | *.03* |
| SLC vs. DCS: 2-Back vs. 3-Back | 0.06 | 0.27 | 0.24 | .81 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Participant | (Intercept) | 0.62 | 0.79 |
| Trial Type | (Intercept) | 1.54 | 1.24 |

*Table 5.4.8: GLMM results of error analysis of N-Back task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

*GLMM.* A generalized linear mixed model (GLMM) was conducted to examine the effects of language context, task condition, and their interactions on error rates.

Random effects analysis indicated substantial variance across participants (Variance = 0.62, SD = 0.79), and trial types (Variance = 1.54, SD = 1.24), suggesting that individual differences and trial-specific factors contributed to the observed variability in error rates.

For the fixed effect of language context, no significant differences were observed between the various levels of LC. Dual LC group had lower accuracy than Single LC group and Dense CSC group. Dense CSC group had lower accuracy than Single LC group.

In contrast, task condition differences revealed significant findings. While the 1-Back vs. 2-Back comparison was not significant, substantial differences emerged between the 1-Back and 3-Back tasks, having an estimated difference of 1.35 (SE = 0.20, z = 6.86), $p < .001$; between the 2-Back and 3-Back tasks, with an estimate of 1.44 (SE = 0.20, z = 7.35), $p < .001$. These results suggest significantly higher error rates in the 3-Back condition compared to the simpler tasks.

Response time (RT) also significantly predicted errors, with slower responses associated with lower error probabilities, with an estimate of 0.25 (SE = 0.05, z = −5.16), with $p < .001$.

Significant interactions were found between language context and task conditions. For the 1-Back vs. 2-Back comparison, DLC vs. SLC showed a significant interaction, with an estimate of 0.86 (SE = 0.32, z = 2.68), where $p = .007$; the Single LC group vs. Dense CSC group contrast also reached significance, with an estimate of 0.84 (SE = 0.32, z = −2.62), with $p = .009$. Dual LC group vs. Dense CSC group interaction was non-significant.

For the 1-Back vs. 3-Back comparison, the interaction between DLC and SLC was not significant. However, significant interactions were observed between Dual LC group and Dense CSC group, with an estimate of 0.58 (SE = 0.28, z = −2.06), with $p = .04$, and Single LC group vs. Dense CSC group, with an estimate of 0.77 (SE = 0.29, z = −2.64), with $p = .008$. In the 2-Back vs. 3-Back comparison, significant interactions were found between Dual LC group and Single LC group, with an estimated difference of 0.66 (SE = 0.26, z = −2.53), with $p = .01$, and Dual LC group vs. Dense CSC group had an estimated difference of 0.60 (SE = 0.28, z = −2.12), with $p = .03$. The Single LC group vs. Dense CSC group interaction was not significant.

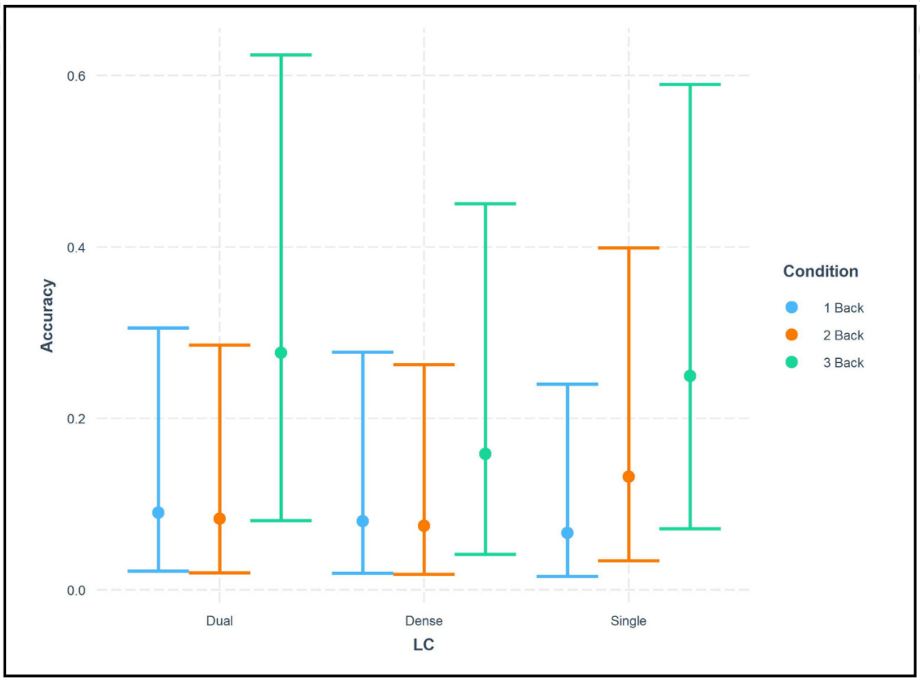


*Figure 5.4.5: Error analysis of each LC group in N-Back task performance. Each coloured bar represents a different task condition.*

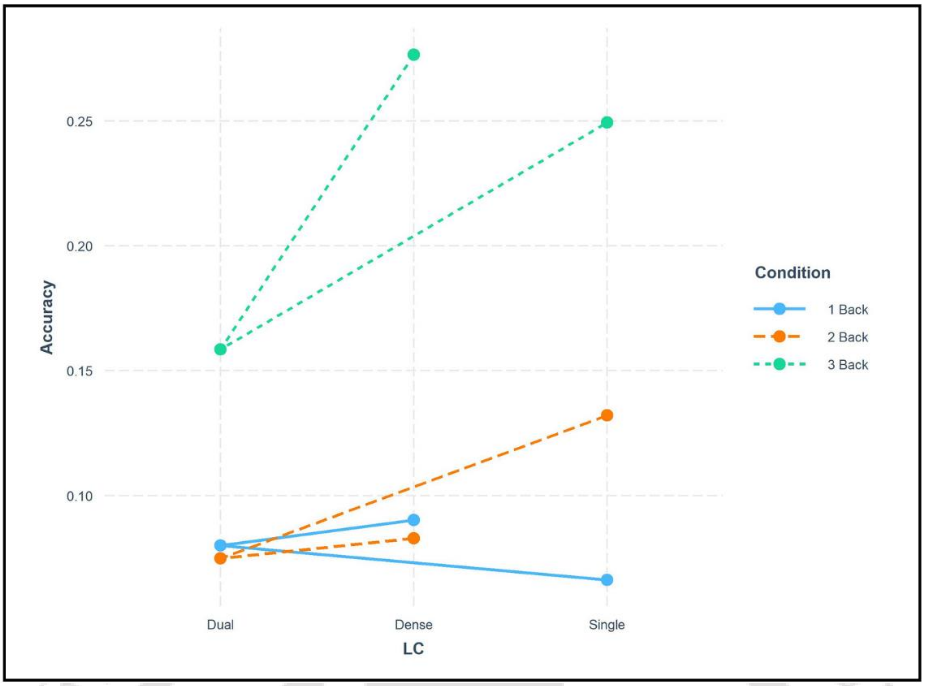


*Figure 5.4.6: Graph showing error analysis of N-Back task performance. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

In summary, task complexity had a significant impact on error rates, with the 3-Back condition exhibiting higher error probabilities than the simpler task conditions. Language context did not exert significance as a main effect, but interacted significantly with task conditions, indicating that the relationship between language context and performance depends on task difficulty. Response time was also a significant predictor, highlighting a link between speed and accuracy.

***Post-error analysis***

A linear mixed-effects model (LMM) was conducted to investigate the influence of language context (LC), task condition, and post-error performance on reaction times (RT).

Random effects analysis indicated considerable variance at the participant level (Variance = 18,738, SD = 136.9) and for post-error trials (Variance = 12,192, SD = 110.4). Trial type variance was also substantial, with a variance of 21,260 (SD = 145.8), along with residual variance of 84,791 (SD = 291.2). The negative moderate correlation (−0.50) between the intercept and post-error random effect suggests that participants with better performance in the task showed a smaller post-error effect.

Post-error trials showed a substantial increase in reaction time, with an estimate of 168.79 *ms* (SE = 40.84, t = 4.13), with $p < .001$, suggesting that participants responded more slowly following an error. In the interaction between post-error performance and LC groups, Dense CSC group showed slower post-error performance than Dual LC group, with an estimated difference of

137.82 *ms* (SE = 49.29, t = -2.80), with *p* = .007. The other interactions did not show statistical significance. Single LC Group showed slower post-error performance than Dual LC group. Dense CSC group showed slower post-error performance than Single LC group.

The post-error x task condition interactions revealed no significant differences in the post-error performance between 1-Back and 2-Back task conditions, where post-error performance in 2-Back condition was slower than 1-Back condition. For the 1-Back vs. 3-Back comparison, the interaction approached significance, with an estimate of 58.41 *ms* (SE = 51.96, t = −1.83), with *p* = .07, with post-error performance in 3-Back condition slower than 1-Back task. The 2-Back vs. 3-Back interaction showed a similar trend, having an estimate of 56.00 *ms* (SE = 30.77, t = −1.82), where *p* = .07, where 3-Back task had slower post-error performance than 2-Back task.

In summary, task difficulty significantly affected reaction times, with the 3-Back condition eliciting the slowest responses. Post-error slowing was evident, particularly influenced by language context in certain comparisons. These findings underscore the complex interplay between task complexity, language context, and error-related adjustments in cognitive performance.

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 795.89 | 90.54 | 2.59 | 8.79 | *.005* |
| Post error | 168.79 | 40.84 | 88.53 | 4.13 | *< .001* |
| ***LC*** | | | | | |
| DLC vs. DCS | 62.30 | 44.25 | 57.99 | 1.41 | .16 |
| DLC vs. SLC | 70.00 | 44.26 | 58.05 | 1.58 | .12 |
| SLC vs. DCS | -7.70 | 43.14 | 58.00 | -0.18 | .86 |
| ***Task condition*** | | | | | |
| 1-Back vs. 2-Back | 98.67 | 8.80 | 6978.99 | 11.21 | *< .001* |
| 1-Back vs. 3-Back | 156.28 | 8.93 | 6978.07 | 17.50 | *< .001* |
| 2-Back vs. 3-Back | 57.61 | 8.99 | 6978.49 | 6.41 | *< .001* |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | -72.28 | 47.55 | 46.90 | -1.52 | .14 |
| Post error: DLC vs. DCS | -137.82 | 49.29 | 4882 | -2.80 | *.007* |
| Post error: SLC vs. DCS | -65.54 | 48.42 | 51.98 | -1.35 | .18 |
| ***Post error x Emotion interaction*** | | | | | |
| Post error: 1-Back vs. 2-Back | -2.41 | 36.13 | 5726.74 | -0.07 | .95 |
| Post error: 1-Back vs. 3-Back | -58.41 | 51.96 | 6107.46 | -1.83 | *.07* |
| Post error: 2-Back vs. 3-Back | -56.00 | 30.77 | 6072.20 | -1.82 | *.07* |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Correlation** |
| Participant | (Intercept) | 18738 | 136.9 | |
| | Post error | 12192 | 110.4 | -0.50 |
| Trial Type | (Intercept) | 21260 | 145.8 | |
| Residual | (Intercept) | 84791 | 291.2 | |

*Table 5.4.9: LMM analysis of post-error performance in N-Back task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

## 5.5 Discussion

This chapter explored the executive control function of working memory. This function is responsible for keeping track of the changes in one's environment, regulating and updating information, so that one can act accordingly.

The hypothesis was that complexity of a bilingual's language switching behaviour would help influence their performance in working memory tasks. In order to examine this, young adult bilinguals performed the N-Back task, and their performance was analysed based on their interactional context behaviour.

The performance of the participants was analysed based on their RT performance and performance accuracy. In RT analysis, it was found that Dual LC group had fastest performance, followed by Dense CSC group and Single LC group, as seen in LMM analysis, EM Means analysis. This difference was not statistically significant, as seen in fixed effects analysis and ANOVA analysis. The task condition showed statistical significance in both, fixed effects and ANOVA analysis. 1-Back condition showed fastest performance, and then 2-Back, and finally 3-Back condition. Accuracy analysis showed 3-Back condition having most errors among the three task conditions. While error-rate analysis showed Dense CSC group having least errors, GLMM showed Single LC group had the least errors. Both analyses showed that Dual LC group had the most errors among the three LC groups. Post-error performance saw Dual LC group having the fastest post-error performance among the three groups, followed by Single LC group and then Dense CSC group.

Thus, results showed that Dual LC group had the fastest RT performance among the three groups, and at the same time, had lowest accuracy among them as per the error analysis. The previous chapter similarly saw the Dual LC group performing better than the other groups in switching tasks. Both of these results aligned with the premise of the Adaptive Control Hypothesis, which stated that the interactional process behind Dual Language Context usage is complex in a way that would require greater exertion of executive control mechanisms. Thus, they would show better performance in tasks that measure the executive control functions.

## 5.6 Chapter summary

This chapter explored how the working memory performance of young adults is influenced by their contextual language usage, using the N-Back task as a measure of working memory performance.

The chapter detailed participant experimental design and tools, methodological approach, the procedure followed, and then the statistical results. The results were then discussed and their implications were expanded upon. Participants with more complex language switching habits showed enhanced working memory performance, supporting the premise put forward by the ACH. These results contribute to the discussion of how bilingualism, more specifically, the language usage patterns of bilinguals help shape their cognitive mechanisms.

The following chapter will look at inhibitory control performance further investigating how contextual language use interacts with various executive control mechanisms.

# 6 Bilingualism and Inhibition

## 6.1 Introduction

The inhibitory control is among the core functions that come under the umbrella of executive control. It involves being able to control one's attention, behaviour and even emotion and direct it towards more goal-oriented behaviour. It curbs the tendency to respond to one's impulses, ignore distractions and engage one's self control towards the task at hand (Diamond, 2013).

Over the years, studies have moved away from examining the executive control as a package deal and paid more focus to inhibitory control, with several theories based on its functioning and its relation to bilingual language control. Green (1998) introduced the inhibitory control model, which emphasized the role of inhibitory control in a bilingual's language processing. According to the model, the inhibitory control mechanism plays an important role in suppressing the language not currently in use, an exercise which gives the bilinguals a cognitive advantage over the monolinguals in their heightened use of the mechanism. It further states that this suppression has various levels, depending upon the context of language usage. For instance, in a code-switching scenario, where the speaker may switch frequently between their languages, the suppression need not be as strong as compared to a when the speaker is in monolingual mode, where they will predominantly use only one language.

In a study by X. Han et al. (2022), Mandarin-English bilinguals from 3 different linguistic scenarios were tested on various cognitive control tasks, including Go/No-go task. Results showed that participants with higher tendency for code-mixing and code-switching showed better inhibitory control performance. Alrwaita et al. (2024) examined the performance of older adults in executive function tasks in a study comparing monolinguals, bilinguals, and diglossics (whose linguistic scenario fits the Single Language Context setting). The participants performed Flanker task, Stroop task and Colour-Shape switching task. Results revealed that diglossics showed an advantage in the Flanker task measuring inhibition, but not in Stroop task.

## 6.2 Chapter overview

In this chapter we look at the executive control mechanism of inhibitory control of young adult bilinguals. Inhibitory control performance was measured using three tasks: Simon task, Stroop task, and Go/No-go task. Each of these tasks measured a different aspect of the inhibitory control. The performance of the participants is examined through the premise of the Adaptive Control Hypothesis. By comparing performances through this paradigm, the chapter tries to identify how bilingual experience of contextual language usage relates to inhibitory control mechanism.

## 6.3 Objective and Hypothesis

The objective of this chapter is to explore the relationship between inhibitory control performances and contextual language usage. The hypothesis was that the more complex the language switching context, better the inhibitory control performance.

## 6.4 Simon task

In a typical Simon task (Simon & Rudell, 1967), two stimuli would appear on the screen one at a time. Each stimulus would have a response key corresponding to it. Ignoring the placement of the stimulus on the screen, the participants had to respond to the stimulus itself. While the location of the stimulus is irrelevant, it has been shown that participants tend to respond slower when the stimulus appears on the side opposite to its corresponding response key (Simon, 1969). This is known as the Simon Effect, which must be inhibited for successful completion of the task.

### 6.4.1 Participants

There were total of 61 participants who took part in the experiment. The participants were all between the ages of 21-35 years ($M_{age}$ = 27.18, SD = 3.64). They were all bilinguals with English as their L2; however, their L1 varied (Assamese, Bangla, Boro, Bhojpuri, Kannada, Kuki, Malayalam, Marathi, Meitei, Mizo, Vaiphei, etc). Hindi was the other language common to all of them.

### 6.4.2 Design and Tools

The questionnaires used in this task were the same as those used in Experiment 2 with switching tasks (Chapter 4) and Experiment 3, with the *N*-back (Chapter 5).

The stimuli consisted of 2 images: a green star and a red triangle (see Figure 1). The participants had to respond to the image regardless of where it is positioned on the screen. There were three positional conditions: Neutral, Congruent, and Incongruent. In Neutral condition, the stimuli were placed on the centre of the screen. In congruent position, the stimuli were on the same side as their corresponding response keys. In Incongruent position, they were positioned in the position opposite to their corresponding response keys. The response keys were ‘A’ and ‘L’; e.g. ‘A’ for green star and ‘L’ for red triangle. The response keys were counterbalanced across participants. The fixation cross (+) was yellow in colour and the images appeared on a black background *(see Figure 6.4.1 for schematic representation)*.

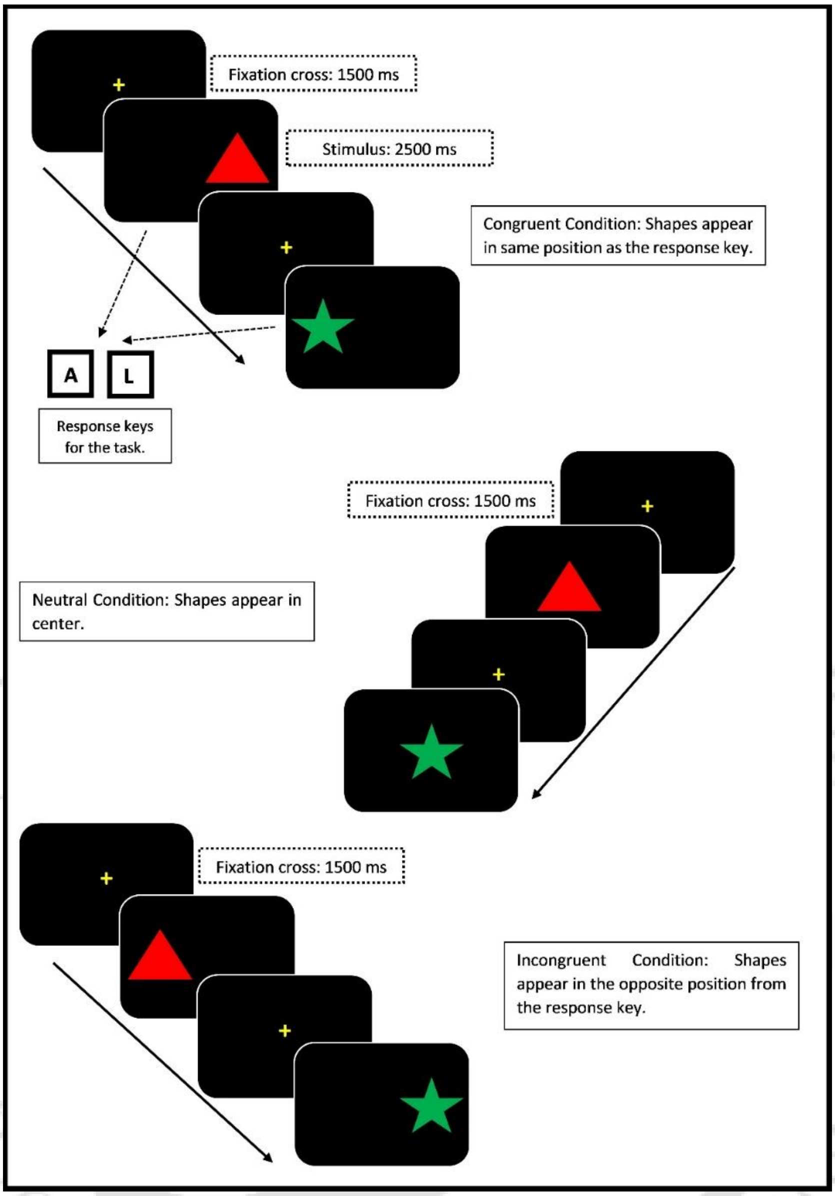


*Figure 6.4.1: Schematic diagram of Simon task performed.*

### 6.4.3 Procedure

The participants filled out the questionnaires and performed the task. The task was created and performed using E-Prime 3 on a 13.3-inch laptop. The participants sat in a quiet room undisturbed to perform the task.

After instructions were displayed, the participants did a practice session followed by the main session. The practice session had 30 trials, whereas the main session had 60 trials. After the instructions, the participants had to perform some trials as practice followed by the main trial. The main trial had all the three conditions, Neutral, Congruent and Incongruent, occurring in a randomized manner for 60 trials. The sequence had a fixation cross (+) appear on the screen first, for 1500 *ms*, followed by the stimulus. In practice sessions, the screen showing the stimulus also had a display showing response keys and their corresponding responses. In the practice trials, the stimulus screen had no time limit and stayed on the screen till a response was recorded. After the practice session, the main session followed in the same pattern. Fixation cross for 1500 *ms*, followed by the stimulus for 2500 *ms*.

### 6.4.4 Results

The questionnaire analysis was the same as for Chapters 4 and 5.

#### 6.4.4.1 Task analysis

The data was analysed on RStudio (R Core Team, 2024). Analysis was done on the response timings as well as accuracy of performance of the participants. The outliers in response time were removed using the interquartile range method.

Using the *lme4* function (Bates et al., 2015) and the *lmerTest* function (Kuznetsova et al., 2017) on RStudio, a linear mixed effects analysis was performed to analyse the relationship between RT and various fixed factors. Models were created with the aim to examine the effect that independent variables, language context (to be referred to as LC henceforth), Task condition and Accuracy, had on the response timings of the participants, as well as the interaction effect the independent (or fixed effects) variables had on each other. This was followed by Type III ANOVA analysis using Satterthwaite's method. The fixed effects included LC (Single LC, Dual LC, and Dense CSC groups), Task condition (Neutral, Congruent, Incongruent), Accuracy (Correct, Error). Random effects included Subject, Display (green star or red triangle), Position (left, right, centre).

Post-HOC analysis of Estimated Marginal Means (Lenth, 2024) and pairwise analysis were also performed to evaluate individual differences between the various levels of the independent variables, as well as the interaction of the independent variables.

Analysis was also done on the accuracy of the participants' performance. A generalised linear mixed model (GLMM) was performed for the error analysis. For this, the RT was scaled and standardised to help the model work more efficiently. An LMM analysis was also done on the post-error performance of the participants, and the interaction between LC and post-error performance as well as task condition and post error performance were also observed.

## *RT analysis*

*Linear mixed-model analysis*

| ***Fixed effects*** | Est. | SE | df | t value | Pr (>\|t\|) |
|---|---|---|---|---|---|
| (Intercept) | 512.64 | 18.40 | 62.30 | 28.36 | < *.001* |
| ***LC*** | | | | | |
| DLC vs. SLC | -4.39 | 25.02 | 66.17 | -0.18 | .86 |
| DLC vs. DCS | -15.05 | 25.03 | 66.29 | -0.60 | .55 |
| SLC vs. DCS | -10.66 | 24.39 | 66.17 | -0.44 | .66 |
| ***Task condition*** | | | | | |
| Congruent vs. Neutral | -9.24 | 9.50 | 4.43 | -0.97 | .38 |
| Congruent vs. Incongruent | -1.92 | 7.90 | 3419.26 | -0.24 | .81 |
| Neutral vs. Incongruent | 7.32 | 9.47 | 4.36 | 0.77 | .48 |
| ***Accuracy*** | | | | | |
| Correct vs. Error | 1.19 | 20.97 | 3432.73 | 0.06 | .95 |
| ***LC x Condition interaction*** | | | | | |
| DLC vs. SLC: Congruent vs. Neutral | -2.43 | 10.84 | 3419.35 | -0.22 | .82 |
| DLC vs. DCS: Congruent vs. Neutral | 39.09 | 10.91 | 3419.36 | 3.58 | *.0003* |
| SLC vs. DCS: Congruent vs. Neutral | 41.52 | 10.61 | 3419.29 | 3.91 | < *.001* |
| DLC vs. DCS: Congruent vs. Incongruent | 10.42 | 10.94 | 3419.46 | 0.95 | .34 |
| DLC vs. SLC: Congruent vs. Incongruent | -0.52 | 10.89 | 3419.30 | -0.05 | .96 |
| SLC vs. DCS: Congruent vs. Incongruent | 10.95 | 10.65 | 3419.63 | 1.03 | .30 |
| DLC vs. SLC: Neutral vs. Incongruent | 1.91 | 10.81 | 3419.12 | 0.18 | .86 |
| DLC vs. DCS: Neutral vs. Incongruent | -28.67 | 10.90 | 3419.41 | -2.63 | *.009* |
| SLC vs. DCS: Neutral vs. Incongruent | -30.58 | 10.62 | 3419.33 | -2.88 | *.004* |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | -17.84 | 33.12 | 3425.67 | -0.54 | .59 |
| DLC vs. DCS: Correct vs. Error | -14.87 | 28.05 | 3431.62 | -0.53 | .60 |
| SLC vs. DCS: Correct vs. Error | 2.97 | 31.68 | 3426.63 | 0.09 | .93 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 5645.97 | 75.14 |
| Display | (Intercept) | 0.00 | 0.00 |
| Position | (Intercept) | 18.84 | 4.34 |
| Shape | (Intercept) | 0.00 | 0.00 |
| Residual | | 11243.57 | 106.04 |

*Table 6.4.1: LMM results of RT analysis of Simon task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed-effects model (LMM) was conducted to investigate the influence of language context (LC), task condition, and accuracy on reaction times (RTs), including their interactions. The model accounted for random intercepts across participants, Display (green star or red triangle), positions (left, right or centre), and shapes (star or triangle).

The random effects analysis revealed substantial variability across participants (Variance = 5645.97, SD = 75.14), indicating significant individual differences in baseline RTs. There was a small but notable variance in position (Variance = 18.84, SD = 4.34), while no variability was detected across displays or shapes, suggesting consistent performance across these factors. The residual variance was 11243.57 (SD = 106.04), reflecting within-subject variability not accounted for by the fixed effects.

Comparisons between the LC groups all showed no statistical significance in the differences between their RTs. Both Dense CSC group and Single LC group were faster than Dual LC group. Analysis showed Dense CSC group had faster performance than Single LC, with an estimated difference of 10.66 *ms* (SE = 24.39, t = -0.44), with $p = .66$. The fixed effect of task condition also showed no significant differences when their comparing performances, where Neutral and Incongruent conditions showed faster performance than Congruent condition and Neutral condition was faster than Incongruent condition. Post-HOC analysis will further explore these differences in the next section. Similarly, there was no significant effect of accuracy on the task performance, suggesting that accuracy did not significantly influence RTs. This would be examined in detail in the Accuracy section.

Interestingly, while no significant interactions were observed in the interaction between LC and accuracy, several significant interactions were observed between the levels LC and task conditions.

The LC × Condition interaction revealed that DLC vs. DCS in the congruent vs. neutral contrast was significant, with an estimate of 39.09 *ms*, (SE = 10.91, t = 3.58), with $p = .0003$, Similarly, when comparing Dense CSC group with Single LC group, there was an estimated difference of 41.52 *ms* (SE = 10.61, t = -3.91), with $p < .001$. For neutral vs. incongruent trials, the comparison between Dual LC group and Dense CSC group was significant, with an estimated difference of 28.67 *ms* (SE = 10.90, t = -2.63), with $p = .009$, while comparison between Dense CS group and Single LC group also showed a significant difference, with an estimate of 30.58 *ms* (SE = 10.62, t = 2.88), with $p = .004$.

Overall, while main effects of language context, task condition, and accuracy were not significant, interactions between language context and task condition revealed meaningful differences, particularly in neutral task condition. These results suggest that LC may moderate RTs in specific task conditions.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| **LC** | 2757 | 1379 | 2 | 109.6 | 0.12 | .88 |
| **Condition** | 2476 | 1238 | 2 | 2.0 | 0.11 | .90 |
| **Accuracy** | 6613 | 6613 | 1 | 3428.4 | 0.59 | .44 |
| **LC: Condition** | 228644 | 57161 | 4 | 3419.4 | 5.08 | *.0004* |
| **LC: Accuracy** | 4361 | 2180 | 2 | 3429.6 | 0.19 | .82 |

*Table 6.4.2: Type III Analysis of Variance Table with Satterthwaite's method of Simon task performance.*

A Type III Analysis of Variance (ANOVA) using Satterthwaite's method was conducted to evaluate the effects of language context (LC), task condition, accuracy, and their interactions on reaction times (RTs). The main effect of LC was not statistically significant, F(2, 109.6) = 0.12, with $p$ = .88, indicating that LC groups did not significantly influence RTs. Similarly, the main effect of condition was not significant, F(2, 2.0) = 0.11, with $p$ = .90, suggesting that task condition (congruent, neutral, incongruent) did not meaningfully affect RTs. The effect of accuracy (correct vs. error) was also non-significant, F(1, 3428.4) = 0.59, $p$ = .44, indicating that RTs did not differ based on task accuracy.

However, the interaction between LC and condition was significant, F(4, 3419.4) = 5.08, $p$ = .0004, suggesting that the relationship between LC and RTs depended on the task condition. No significant interaction was found between LC and accuracy, F(2, 3429.6) = 0.19, $p$ = .82, indicating that the effect of LC on RTs did not vary as a function of accuracy.

In summary, while no significant main effects of LC, condition, or accuracy were found, the significant LC by condition interaction highlights the presence of a relationship between these factors, suggesting that LC grouping affects performance of RTs across task conditions.

***Post-HOC analysis***

*EM Means- Language context*

An estimated marginal means analysis was conducted to compare reaction times across different language contexts (LC): Single, Dual, and Dense *(see Figure 6.4.2 for graphical representation)*. The results revealed that the Single LC group had the fastest performance, with an estimated mean RT of 504 *ms* (SE = 21.0, df = 132.1, 95% CI [463, 546]). Next came Dense CSC group with an estimated mean of 513 *ms* (SE = 19.0, df = 90.1, 95% CI [475, 550]). Finally, the Dual LC group had the slowest performance with a mean estimated to be 519 *ms* (SE = 20.3, df = 97.4, 95% CI [476, 559]) *(see table 6.4.3)*.

While there are slight differences in the mean RTs across the three language contexts, with Dual LC group having the highest mean RT, these estimates include overlapping confidence intervals, suggesting that any differences between the language contexts may not be statistically meaningful. This is further explored in the pairwise analysis.

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 504 | 21.0 | 132.1 | 463 | 546 |
| ***Dual*** | 519 | 20.3 | 97.4 | 478 | 559 |
| ***Dense*** | 513 | 19.0 | 90.1 | 475 | 550 |

*Table 6.4.3: Group-wise EM Means based on Language Context in Simon task.*

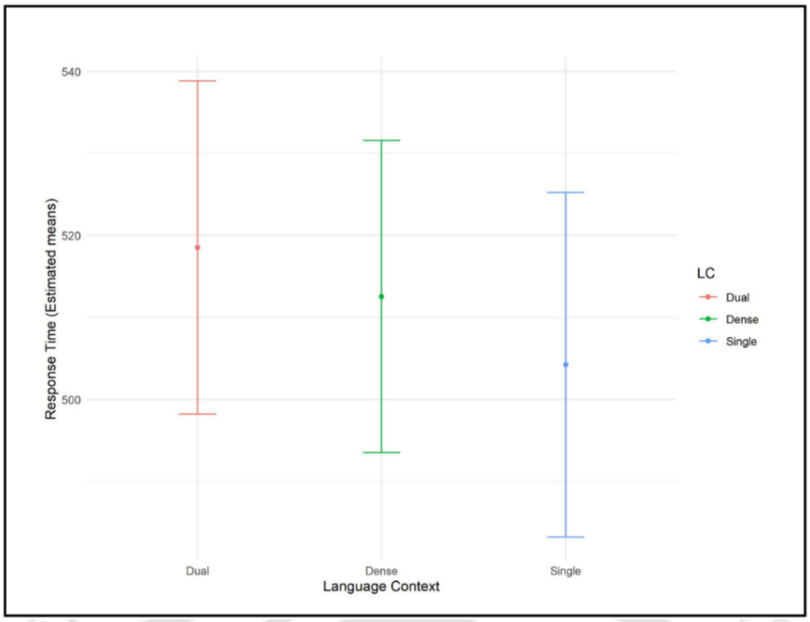


*Figure 6.4.2: Group-wise EM Means performance based on Language Context in Simon task performance. Single LC group shows the least EM means, followed by Dense CSC group, which is followed by Dual LC group. Bars represent 95% confidence intervals.*

*Pairwise analysis- Language context*

A pairwise comparison analysis was conducted to examine differences in reaction times across the three language contexts groups *(see table 6.4.4)*. The contrast between the Dual LC and Dense CSC groups revealed a non-significant difference of 5.98 *ms* (SE = 27.6, df = 97.8, t = 0.22), with $p$ = .97. Similarly, the difference between the Dense CSC and Single LC groups was non-significant, with a difference of 8.32 *ms* (SE = 28.1, df = 115.8, t = 0.30), with $p$ = .95. The contrast between the Dual and Single contexts also did not reach significance, having an estimated difference of 14.30 *ms* (SE = 29.0, df = 118.5, t = 0.49), with $p$ = .88.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | 5.98 | 27.6 | 97.8 | 0.22 | .97 |
| ***Dense - Single*** | 8.32 | 28.1 | 115.8 | 0.30 | .95 |
| ***Dual - Single*** | 14.30 | 29.0 | 118.5 | 0.49 | .88 |

*Table 6.4.4: Pair-wise analysis based on Language context in Simon task performance.*

These results indicate that no significant pairwise differences were observed between the Dual, Dense, and Single LC groups. Although the estimates suggest some variation in RTs, these differences are small and not statistically meaningful, as indicated by the high p values across all contrasts.

*EM Means- Task condition*

EM Means analysis conducted examined the participants' performance across three different task conditions: Neutral, Congruent, and Incongruent. Congruent task condition had the fastest mean

RT, with an estimated mean of 510 *ms* (SE = 12.2, df = 59.0, 95% CI [486, 535]). Performance in Incongruent condition came next, with an estimated mean of 512 *ms* (SE = 12.1, df = 57.2, 95% CI [487, 536]). Interestingly, Neutral task condition had the slowest performance, with a mean RT of 513 *ms* (SE = 12.6, df = 25.2, 95% CI [487, 539]).

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Neutral*** | 513 | 12.6 | 25.2 | 487 | 539 |
| ***Congruent*** | 510 | 12.2 | 59.0 | 486 | 535 |
| ***Incongruent*** | 512 | 12.1 | 57.2 | 487 | 536 |

*Table 6.4.5: Group-wise EM Means based on task condition in Simon task performance.*

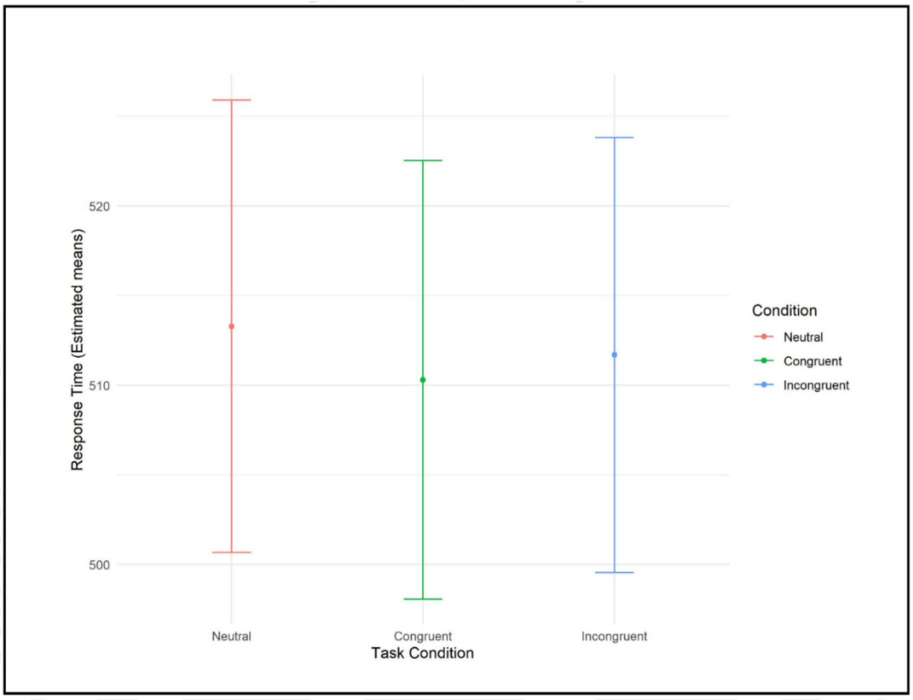


*Figure 6.4.3: Group-wise EM Means performance based on task condition in Simon task performance. Performance in Congruent task condition was the fastest, followed by Incongruent condition, closely followed by Neutral task condition. Bars represent 95% confidence intervals.*

The estimated marginal means suggest minimal differences in RTs across the three conditions, with all mean RTs falling within a narrow range between 510 - 513 *ms*. Furthermore, the overlapping confidence intervals indicate that these differences are unlikely to be statistically significant.

*Pairwise analysis- Task condition*

A pairwise comparison analysis was conducted to examine differences in reaction times (RTs) between the task conditions: Neutral, Congruent, and Incongruent.

Comparing Neutral and Congruent conditions revealed a non-significant difference of 2.98 *ms* (SE = 6.90, df = 1.22, t = 0.43), with $p$ = *NaN*. Similarly, the difference between the Neutral and Incongruent conditions was also not significant, with an estimate of 1.60 *ms* (SE = 6.90, df = 1.22, t = 0.23), with *p* = *NaN*. Lastly, the contrast between the Congruent and Incongruent conditions also showed no significant difference, having an estimated difference of -1.38 *ms* (SE = 4.42, df = 1.02, t = -0.31), with *p* = *NaN*.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Neutral - Congruent*** | 2.98 | 6.90 | 1.22 | 0.43 | *NaN* |
| ***Neutral - Incongruent*** | 1.60 | 6.90 | 1.22 | 0.23 | *NaN* |
| ***Congruent - Incongruent*** | -1.38 | 4.42 | 1.02 | -0.31 | *NaN* |

*Table 6.4.6: Pair-wise analysis based on task condition in Simon task performance.*

These results indicate that there were no statistically significant differences in RTs between any of the task conditions. The t ratios and non-calculable p values (*NaN* = Not a Number) suggest that the observed differences are not meaningful, further reinforcing the minimal variation in RTs across conditions. The occurrence of *NaN* for p-value suggests a computational issue, often due to insufficient degrees of freedom or data irregularities. In this case, the degrees of freedom (df = 1.02-1.22) are extremely low, which could explain the inability to calculate a proper p-value.

In summary, the pairwise analysis shows no significant differences in RTs between Neutral, Congruent, and Incongruent conditions, implying that task condition does not substantially affect reaction times. The presence of non-numerical values for p-value indicates that the model might have faced difficulties in reliably estimating the contrasts due to the limited degrees of freedom or data characteristics.

*EM Means- LC x Task condition*

An EM Means analysis was conducted to examine reaction times across different language contexts and task conditions.

In Neutral task condition, Single LC group had the fastest mean RT of 497 *ms* (SE = 21.8, df = 101.9, 95% CI [454, 540]). Dual LC group came next with an average mean of 513 *ms* (SE = 21.2, df = 81.5, 95% CI [471, 555]). Dense CSC group showed the slowest performance in this task condition with an estimated mean of 530 *ms* (SE = 19.9, df = 71.5, 95% CI [490, 569]).

In Congruent task condition, Dense CSC group had the fastest performance, with an estimated mean of 500 *ms* (SE = 19.6, df = 94.0, 95% CI [461, 539]). They were followed by Single LC group having a mean RT of 509 *ms* (SE = 21.6, df = 138.0, 95% CI [466, 552]). Finally, Dual LC group displayed an average RT of 522 *ms* (SE = 21.0, df = 104.2, 95% CI [481, 564]).

In Incongruent task condition, Single LC group had the least mean RT of 506 *ms* (SE = 21.3, df = 130.8, 95% CI [464, 549]). Dense CSC group had an estimated mean of 508 *ms* (SE = 19.6, df

= 94.5, 95% CI [469, 547]). Dual LC group had a mean RT of 520 *ms* (SE = 20.7, df = 99.7, 95% CI [479, 561]).

| LC | Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Neutral*** | 497 | 21.8 | 101.9 | 454 | 540 |
| ***Dual*** | ***Neutral*** | 513 | 21.2 | 81.5 | 471 | 555 |
| ***Dense*** | ***Neutral*** | 530 | 19.9 | 71.5 | 490 | 569 |
| ***Single*** | ***Congruent*** | 509 | 21.6 | 138.0 | 466 | 552 |
| ***Dual*** | ***Congruent*** | 522 | 21.0 | 104.2 | 481 | 564 |
| ***Dense*** | ***Congruent*** | 500 | 19.6 | 94.0 | 461 | 539 |
| ***Single*** | ***Incongruent*** | 506 | 21.3 | 130.8 | 464 | 549 |
| ***Dual*** | ***Incongruent*** | 520 | 20.7 | 99.7 | 479 | 561 |
| ***Dense*** | ***Incongruent*** | 508 | 19.6 | 94.5 | 469 | 547 |

*Table 6.4.7: Group-wise EM Means based on interaction between LC and task condition in overall performance in Simon task performance.*

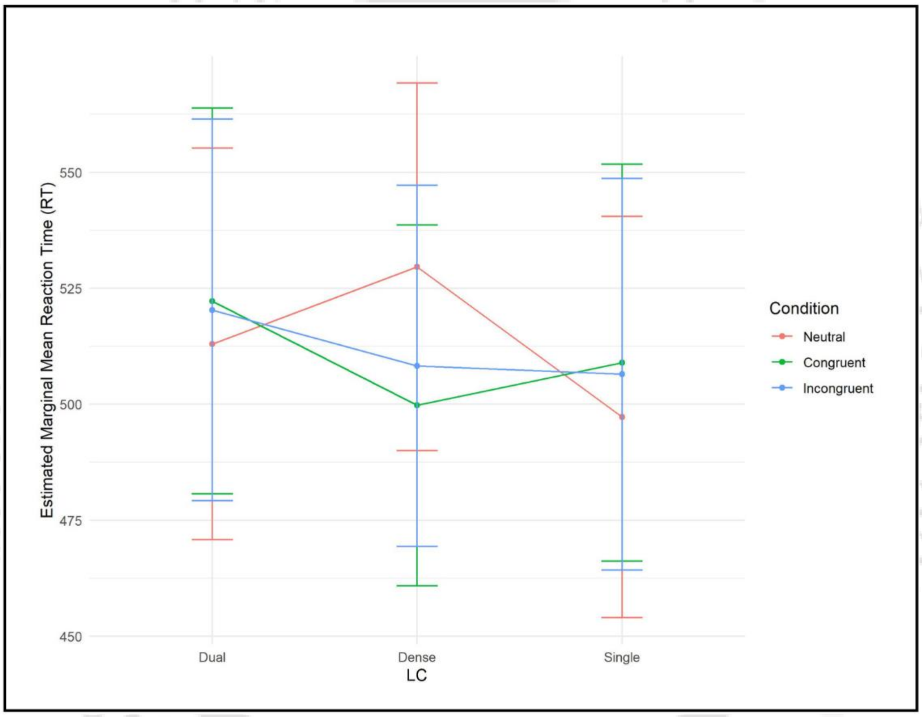


*Figure 6.4.4: Interaction of LC x Task condition in Simon task performance.*

Overall, the results indicate slight differences in RTs across the language contexts and conditions. Single LC group generally showed least mean RT in Neutral and Incongruent conditions, Dual LC group almost consistently showed higher mean RTs than the other two LC groups. However, the confidence intervals for these estimates overlap, suggesting that the differences between language contexts and conditions may not be statistically significant.

### *Accuracy analysis*

*Error rate.* Single LC group had the least errors (1.48%), followed by Dual LC group (2.56%), and then Dense CSC group (2.96%).

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| (Intercept) | -4.70 | 0.53 | 08.79 | < *.001* |
| ***LC*** | | | | |
| DLC vs. SLC | -0.42 | 0.76 | -0.55 | .58 |
| DLC vs. DCS | 0.56 | 0.66 | 0.85 | .40 |
| DCS vs. SLC | -0.98 | 0.71 | -1.38 | .17 |
| ***Task condition*** | | | | |
| Neutral vs. Congruent | 0.22 | 0.59 | 0.37 | .71 |
| Neutral vs. Incongruent | 0.99 | 0.52 | 1.92 | *.05* |
| Congruent vs. Incongruent | 0.78 | 0.50 | 1.58 | .51 |
| ***Response time*** | | | | |
| RT (scaled) | -0.10 | 0.13 | -0.80 | .42 |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Neutral vs. Congruent | -0.48 | 0.96 | -0.51 | .61 |
| DLC vs. DCS: Neutral vs. Congruent | 0.04 | 0.72 | 0.06 | .96 |
| DCS vs. SLC: Neutral vs. Congruent | -0.52 | 0.89 | -0.59 | .55 |
| DLC vs. SLC: Neutral vs. Incongruent | 0.06 | 0.77 | 0.07 | .94 |
| DLC vs. DCS: Neutral vs. Incongruent | -0.80 | 0.67 | -1;20 | .23 |
| DCS vs. SLC: Neutral vs. Incongruent | 0.86 | 0.74 | 1.16 | .25 |
| DLC vs. DCS: Congruent vs. Incongruent | -0.84 | 0.63 | -1.34 | .18 |
| DLC vs. SLC: Congruent vs. Incongruent | 0.54 | 0.81 | 0.67 | .51 |
| DCS vs. SLC: Congruent vs. Incongruent | 1.38 | 0.78 | 1.78 | *.08* |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 1.12 | 1.06 |
| Display | (Intercept) | 0.02 | 0.14 |
| Position | (Intercept) | 0.00 | 0.00 |

*Table 6.4.8: GLMM results of error analysis of Simon task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

*GLMM.* A generalized linear mixed-effects model (GLMM) was conducted to analyse error rates as a function of language context (LC), task condition, and response time (RT), while accounting for random effects across participants, display, and position of stimulus. The random intercept for participants showed some variability (Variance = 1.12, SD = 1.06), but minimal variability was observed for display (Variance = 0.02, SD = 0.14), and no variability for position (Variance = 0.00).

For the fixed effects, the main effect of language context (LC) revealed no significant differences between the LC groups, where Dual LC and Dense CSC groups had lower accuracy than Single LC group, and Dense CSC group had lower accuracy than Dual LC group. This lack of significance suggested that language context did not significantly affect error rates.

For the main effect of task condition, accuracy was shown to be lower for Congruent condition than Neutral and for Incongruent condition that for Congruent condition. These differences were not statistically significant. However, the difference between the Neutral and Incongruent conditions showed significance, with an estimate of 0.99 (SE = 0.52, z = 1.92), with *p* = .05, indicating that participants were significantly more likely to make errors in the Incongruent condition compared to the Neutral condition.

Response time, when scaled, was not a significant predictor of errors, showing an estimate of -0.10, (SE = 0.13, z = -0.80), with *p* = .42, suggesting that response timing did not meaningfully influence error rates. Similarly, there were no significant interactions between LC and task condition, except when comparing Dense CSC group and Single LC group, when comparing their performance in Congruent and Incongruent conditions, with an estimate of 1.38 (SE = 0.78, z = 1.78), with p = .08, which approached significance.

In summary, this error analysis revealed that while participants were more likely to make errors in the Incongruent condition compared to the Neutral condition, language context (LC) did not significantly impact error rates, nor did response time. Additionally, no significant interactions were found between language context and task condition in relation to error rates.

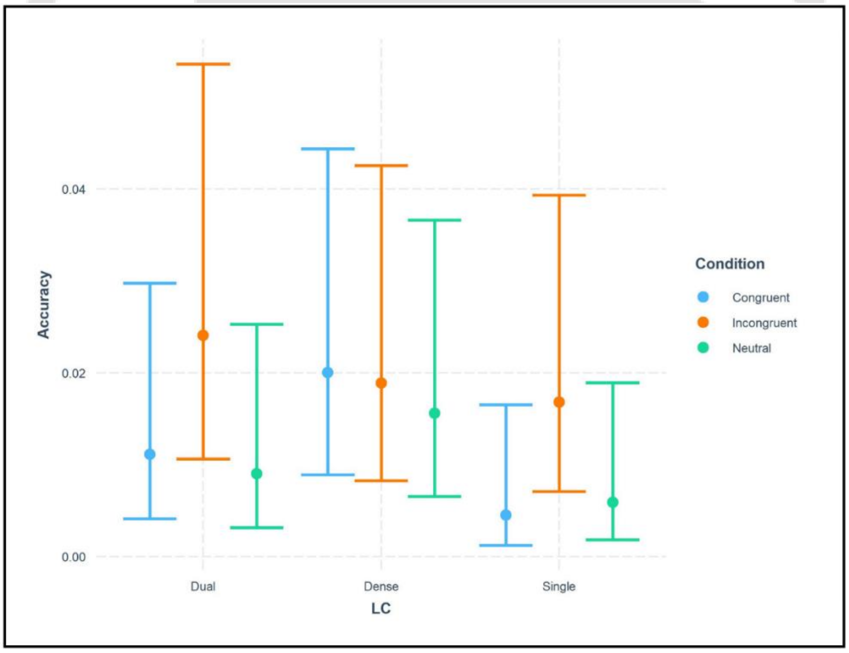


*Figure 6.4.5: Error analysis of each LC group in Simon task performance. Each coloured bar represents a different task condition.*

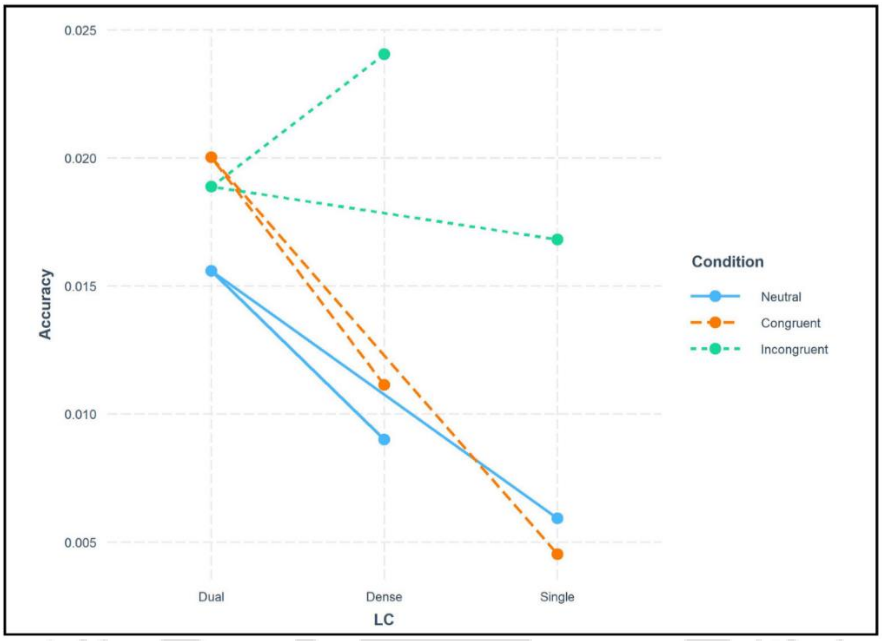


*Figure 6.4.6: Graph showing error analysis of Simon task performance. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

### *Post-Error analysis*

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| (Intercept) | 519.38 | 18.33 | 47.64 | 28.33 | *< .001* |
| Post error | -0.04 | 26.99 | 19.72 | -0.001 | .99 |
| ***LC*** | | | | | |
| DLC vs. SLC | -6.61 | 24.42 | 57.87 | -0.27 | .79 |
| DLC vs. DCS | -0.28 | 24.43 | 57.95 | -0.01 | .99 |
| DCS vs. SLC | -6.33 | 23.81 | 57.91 | -0.27 | .79 |
| ***Task condition*** | | | | | |
| Neutral vs. Congruent | -2.62 | 6.64 | 1.29 | -0.40 | .75 |
| Neutral vs. Incongruent | -1.84 | 6.63 | 1.28 | -0.28 | .82 |
| Congruent vs. Incongruent | 0.78 | 4.45 | 3388.31 | 0.18 | .86 |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | 62.33 | 38.52 | 17.64 | 1.62 | .12 |
| Post error: DLC vs. DCS | 35.73 | 34.57 | 12.30 | 1.03 | .32 |
| Post error: DCS vs. SLC | 26.60 | 23.81 | 57.91 | -0.27 | .79 |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Neutral vs. Congruent | -7.41 | 29.97 | 274.55 | -0.25 | .81 |
| Post error: Neutral vs. Incongruent | 47.85 | 32.18 | 271.50 | 1.49 | .14 |
| Post error: Congruent vs. Incongruent | 55.26 | 35.40 | 268.54 | 1.56 | .12 |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Correlation** |
| Subject | (Intercept) | 5750.72 | 75.83 | |
| | Post error | 1711.22 | 41.36 | -0.47 |
| Position | (Intercept) | 16.19 | 4.02 | |
| Residual | | 11225.04 | 105.95 | |

*Table 6.4.9: LMM results of post-error performance in Simon task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed-effects model (LMM) was employed to examine the effects of post-error responses on participants' responses, incorporating random effects for participant variability and position. The random intercepts for participants (Variance = 5750.72, SD = 75.83), and post-error (Variance = 1711.22, SD = 41.37), showed substantial variability. The negative correlational value (-0.47) indicating a negative relationship between post-error responses and RTs, where those with slower responses had smaller post-error effects and those who responded faster had a greater post-error slowing.

While post-error responses were faster than those after correct responses with an estimated difference of 0.04 *ms* (SE = 26.99, t = -0.001), with $p = .99$, but this difference in performance was not significant.

The interaction between post-error performance and LC group showed that post-error performance was slower for Dual LC group than for Single LC and Dense CSC groups. Dense CSC group had slower post-error performance than Single LC group. These differences were not statistically significant. In the interaction between post-error performance and task condition, Incongruent condition showed faster post-error performance than Neutral and Congruent conditions. Congruent condition was slower post-error than Neutral condition. These differences were similarly not statistically significant.

In summary, the post-error analysis revealed that while there were no significant effects of post-error responses or interactions with language context and task conditions on RTs, the findings indicate a complex relationship between post-error responses and subsequent performance.

### 6.4.5 Discussion

The aim of this experiment was to examine the performance of bilinguals in Simon task, a task commonly used to measure inhibitory control, based on their language usage context. The hypothesis was that the participants used to switching languages within a context with changing interlocuters or circumstances, prevalent in Dual-language context, would exhibit greater inhibitory control and have better performance, than Single-language context or Dense code-switching context, in a task that requires the same control processes.

Results of the post-HOC analysis showed that the overall performance of the three language context groups showed Single LC group to be the fastest, followed by Dense CSC group, and then finally the Dual LC group. The overall performance in Congruent task condition was fastest, followed by Incongruent condition, which was very closely followed by Neutral task condition. However, the difference between the three task conditions were miniscule, at best. Linear Mixed-effects analysis showed that none of the main effects showed statistical significance, ANOVA using Satterthwaite's method showed no statistical significance for any fixed effects or interaction of fixed effects. Interestingly, the interaction between LC and task condition shows statistical significance, specifically when comparing performance between Dense CSC group with Dual LC and Single LC groups, while comparing their performances in Neutral condition with Congruent and Incongruent conditions. Thus, the performance difference between LC groups is specifically seen when comparing with Dense CSC group and with Neutral task condition.

An interesting observation was that the differences among the Language Context groups was different for the Linear Mixed-Model analysis and EM Means analysis in the RT performance. LMM analysis had Dense CSC group performing faster than Dual LC group and Single LC group, and Single LC group faster than Dual LC group. EM Means analysis showed Single LC group having lowest EM Means, followed by Dense CSC group and then Dual LC group. This difference in the outcome could be because of the methodology applied by both the analysis. While LMM takes into account the random effects EM Means analysis provides more of an overall estimate. Since the difference between the LC groups were minimal, this methodological difference was more evident.

The error analysis showed that while participants were more likely to make errors in the Incongruent condition compared to the Neutral condition, language context (LC) did not significantly impact error rates, nor did response time. Additionally, no significant interactions were found between language context and task condition in relation to error rates. Similarly, post-error analysis revealed that in terms of language context, no significant differences were observed between the different LC groups. Similarly, the analysis of task condition revealed no significant differences. Interactions between post-error responses and language context were explored but did not yield significant results, and no significant interactions were found between post-error responses and task conditions. Thus, across language context groups and task conditions, the participants' post-error performance was not significantly affected by task accuracy.

The results of this task were unexpected, based on the assumption of the ACH. Firstly, the results of the task did not abide by the Adaptive Control Hypothesis. The overall performance showed Single LC group outperforming the other groups, with Dense CSC group close behind. Most of the factors did not show statistical significance. A brief review of the latest literature would show that when it comes to examining the bilingual advantage through Simon task, the outcomes are mixed, at best (Bellegarda & Macizo, 2021; Champoux-Larsson & Dylman, 2021; Dash et al., 2021; Privitera et al., 2023). Analysis have shown lack of significance in the comparisons, and no clear outcome of difference in performances between groups compared. To reaffirm 2 more experiments were performed, both with inhibitory control tasks.

## 6.5 Stroop task

The Stroop task (Stroop, 1935) has been widely used to study inhibition and attentional control. This task involves ignoring the word and respond to the colour of the text. The human brain is trained to respond to the meaning of the text and inhibit reacting to superficial characteristics such as font or colour of the text (Diamond, 2013). When forced to ignore the meaning of the word and respond instead to the colour of the text, people tend to be slower and have more errors.

### 6.5.1 Participants

This experiment, in order to overcome any possible methodological issues that might have impacted the previous experiment, fine-tuned the participant pool. For instance, the size of the sample was increased to one hundred and seven (107) and the age range of the participants was narrowed to 18-25 ($M_{age}$ = 19.49, SD = 1.31). They were all students of Indian Institute of Technology, pursuing their Bachelor's degree in various STEM fields. The participants were all at least bilinguals, from various parts of the country, with knowledge of minimum 2 languages, Hindi and English. Some participants also spoke a third language like Assamese, Bangla, Bhojpuri, Harayanvi, Kannada, Malayalam, Marathi, Marwari, Mewari, Mizo, Punjabi, Rajastani, Telugu, Urdu, etc.

### 6.5.2 Design and tools

The questionnaire used for this experiment included questions from Language Experience And Proficiency Questionnaire (LEAP-Q) (Marian et al., 2007), Language History Questionnaire (LHQ 3) (P. Li et al., 2020), from (Rodriguez-Fornells et al., 2012) *(see Appendix C)*, and a questionnaire based on *Revised Bilingual Interactional Questionnaire* from (Hartanto & Yang, 2020) *(Appendix D)*.

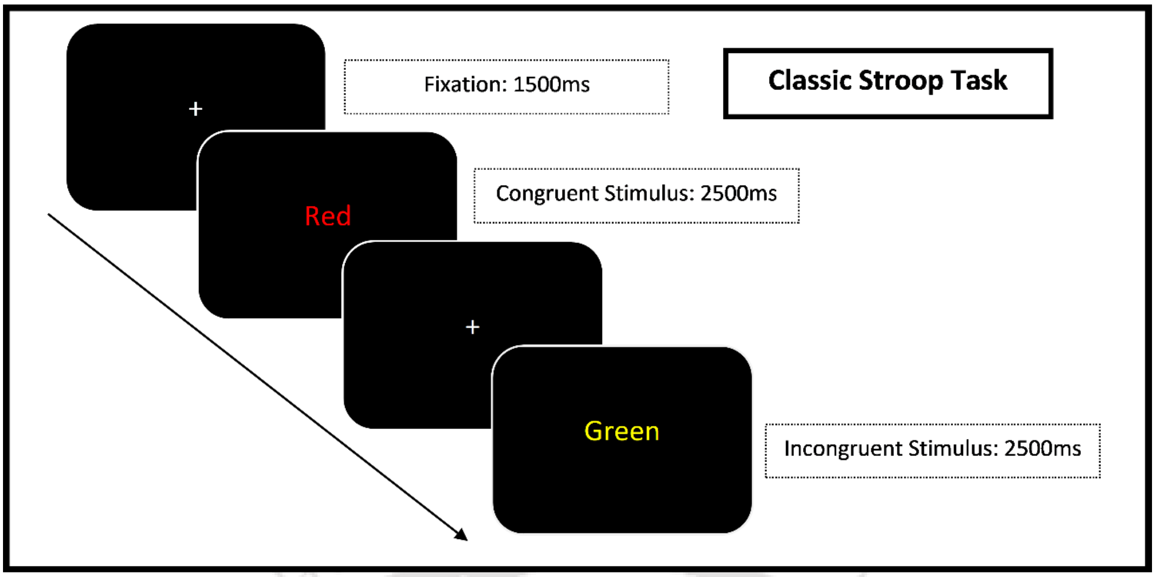


*Figure 6.5.1: Schematic diagram of Stroop task performed.*

The task was created on E-Prime 3. There were two blocks: a practice block and a main block. The practice block had 'XXXX' displayed at the center in 4 different colors and the participants had to respond to the colour of the display. The main block had the names of the 4 colors written and the participants had to ignore the text and only respond to the colour. The colors were: Red, Blue, Green, and Yellow. There were two task conditions: congruent and incongruent. The congruent trials had the text and the colour of the text in the same colour ('Blue' written in blue). The incongruent trials will have mismatched text and text colour (e.g., 'Blue' written in green).

### 6.5.3 Procedure

In this task, participants were presented with colour names in 4 different colors on a black background and the participants have to ignore the word and respond just to the colour of the word displayed.

The participants performed the task and filled out the questionnaires (same as before) aimed at getting the background information about the participants, with regard to language switching behaviour and general language history. The task was performed on a 13.3-inch laptop.

There was a practice session, followed by the main session. The main session consisted of 100 trials, where all the four colours were displayed equally. Since the aim of this experiment was to observe the inhibitory control's conflict monitoring control and thus the congruent-incongruent split was 20-80, 20% of the trials were congruent, and 80% incongruent trials. This would result in slower performance in congruent trials, and faster performance in incongruent trials, resulting in a reduced Stroop effect as participants would employ cognitive strategies to anticipate incongruent trials (Maclellan et al., 2006).

The stimulus was displayed on a black background. First, a fixation cross appeared on the screen for 1500 *ms*, followed by the stimulus, which stayed on the screen till a response was given or for 2500 *ms*, whichever occurred first *(see Figure 6.51 for schematic of the task)*. The participants had to respond to the colour of the text on the screen, and ignore the word written. The response was recorded using Chronos, a response collecting instrument often used in tandem with E-Prime.

### 6.5.4 Results

#### 6.5.4.1 Questionnaire analysis

The data from the questionnaire helped divide the participants into three groups: Single LC group (47 participants), Dual LC group (31 participants), and Dense Code-switching group (29 participants).

#### 6.5.4.2 Task analysis

***RT analysis***

*Linear mixed-model analysis*

| ***Fixed effects*** | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
|---|---|---|---|---|---|
| (Intercept) | 743.66 | 30.08 | 13.94 | 24.72 | *< .001* |
| ***LC*** | | | | | |
| DLC vs. SLC | -29.15 | 28.76 | 107.83 | -1.01 | .31 |
| DLC vs. DCS | -27.01 | 31.97 | 107.84 | -0.85 | .40 |
| DCS vs. SLC | -2.14 | 29.34 | 107.84 | -0.07 | .94 |
| ***Task condition*** | | | | | |
| Congruent vs. Incongruent | 61.47 | 5.79 | 9970.60 | 10.62 | *< .001* |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -43.42 | 20.16 | 9979.84 | -2.15 | *.03* |
| ***LC x Condition interaction*** | | | | | |
| DLC vs. SLC: Congruent vs. Incongruent | 5.34 | 7.49 | 9970.67 | 0.71 | .48 |
| DLC vs. DCS: Congruent vs. Incongruent | -8.15 | 8.31 | 9970.44 | -0.98 | .33 |
| DCS vs. SLC: Congruent vs. Incongruent | 13.50 | 7.63 | 9970.12 | 1.77 | *.08* |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | 35.45 | 23.99 | 9981.42 | 1.48 | .14 |
| DLC vs. DCS: Correct vs. Error | 25.08 | 27.25 | 9980.87 | 0.92 | .36 |
| DCS vs. SLC: Correct vs. Error | 10.37 | 22.49 | 9987.30 | 0.46 | .64 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 14697.77 | 121.23 |
| Stimulus | (Intercept) | 6.04 | 2.46 |
| Colour | (Intercept) | 1636.62 | 40.46 |
| Residual | | 23761.57 | 154.15 |

*Table 6.5.1: LMM results of RT analysis of Stroop task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed model (LMM) analysis was conducted to assess the effects of language context (LC), task condition (Congruent vs. Incongruent), and accuracy (Correct vs. Error) on reaction times (RTs) in the Stroop task. The model included random intercepts for subjects, stimuli, and colour categories, accounting for individual differences and stimulus variability. The variance attributed to subjects was 14,697.77 (SD = 121.23), while the variance for stimuli and colour was 6.04 (SD = 2.46) and 1,636.62 (SD = 40.46), respectively. The residual variance was 23,761.57 (SD = 154.15), indicating considerable unexplained variability in RTs.

The fixed effects analysis revealed that the main effect of language context was not significant. Both, Dense CSC group and Single LC group were faster than Dual LC group. Comparison between Single LC group and Dense CSC group showed that Single LC group was faster than Dense CSC group. All yielded non-significant results, suggesting that language context did not independently affect RTs.

Task condition significantly influenced RTs, with participants responding faster in the Congruent condition compared to the Incongruent condition, with an estimated difference of 61.47 ms (SE = 5.79, t = 10.62), $p$ <.001. This finding further underscores the classic Stroop effect, where congruent trials lead to quicker responses than incongruent ones due to reduced cognitive interference. Accuracy also had a significant main effect, with correct responses being faster than incorrect responses by an estimated difference of 43.42 ms (SE = 20.16, t = −2.15), with $p$ = .03.

The interaction between language context and task condition did not reaches statistical significance. However, the Dense CSC group and Single LC group contrast in Congruent vs. Incongruent condition had an estimate of 13.50 ms (SE = 7.63, t = 1.77), with $p$ = .08, which approached significance. Interactions between LC and Accuracy were non-significant.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| **LC** | 7008 | 3504 | 2 | 136.7 | 0.15 | .86 |
| **Task condition** | 8548537 | 8548537 | 1 | 9970.7 | 359.76 | *< .001* |
| **Accuracy** | 126467 | 126467 | 1 | 9984.3 | 5.32 | *.02* |
| **LC: Task condition** | 74437 | 37219 | 2 | 9970.4 | 1.57 | .21 |
| **LC: Accuracy** | 51842 | 25921 | 2 | 9983.6 | 1.09 | .34 |

*Table 6.5.2: Type III Analysis of Variance Table with Satterthwaite's method for Stroop task performance.*

A Type III Analysis of Variance (ANOVA) was conducted to examine the effects of language context (LC), task condition, and accuracy on reaction times (RT) of the participants. The analysis included the factors of LC, task condition, accuracy, and their interactions.

The results indicated that the main effect of LC was not statistically significant, F(2, 136.7) = 0.15, with $p$ = .86, suggesting that the different language contexts (Dual LC, Single LC, and Dense Code Switching) do not have a meaningful impact on RT. In contrast, the main effect of task condition was significant, F(1, 9970.7) = 359.76, with $p$ < .001, indicating that reaction times were significantly faster for congruent trials compared to incongruent trials. This highlights the influence of task condition on the performance of the participants, with a strong effect size evident in the observed variance.

The accuracy of responses also had a significant main effect on RT, F(1, 9984.3) = 5.32, where $p$ = .02. This finding indicates that error responses were associated with shorter reaction times compared to correct responses, emphasizing the significance of accuracy in performance.

Additionally, the interaction between LC and task condition was not significant, where F(2, 9970.4) = 1.57, with $p$ = .21, suggesting that the influence of language context on RT does not vary across different task conditions. Similarly, the interaction between LC and accuracy was also non-significant, with F(2, 9983.6) = 1.09, $p$ = .34, indicating that the effect of language context grouping does not change based on response accuracy.

In summary, ANOVA results reveal significant effects of task condition and accuracy on reaction times, while the main effects and interactions involving language context were not significant, suggesting that language context may not play a crucial role in influencing RT.

### *Post-HOC analysis*

*EM Means- Language Context*

An Estimated Marginal Means (EM Means) analysis was conducted to evaluate the average reaction times (RT) across the three different language contexts: Single LC, Dual LC, and Dense Code Switching (DCS) groups.

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 744 | 27.8 | 10.4 | 682 | 806 |
| ***Dual*** | 753 | 31.4 | 16.6 | 686 | 819 |
| ***Dense*** | 734 | 31.6 | 17.0 | 667 | 801 |

*Table 6.5.3: Group-wise EM Means based on Language Context in Stroop task performance.*

The results revealed that Dense CSC group with an average estimate of 734 *ms* (SE = 31.6, df = 17.0, 95% CI [667, 801]), showed the fastest average performance among the three groups. They were followed by Single LC, participants exhibited an average RT of 744 *ms* (SE = 27.8, df = 10.4, 95% CI [682, 806]). Dual LC group came last with an estimated average of 753 *ms* (SE = 31.4, df = 16.6, 95% CI [686, 819]).

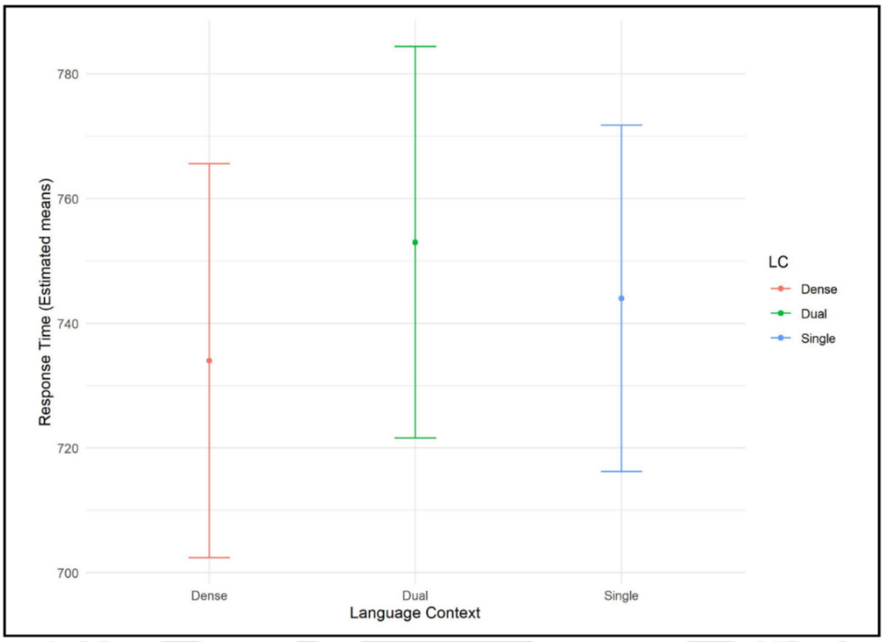


*Figure 6.5.2: Group-wise EM Means performance based on Language Context in Stroop task performance. Dense CSC group shows the least EM means, closely followed by Single LC group, which is followed by Dual LC group. Bars represent 95% confidence interval.*

These findings highlight the variability in reaction times associated with different language contexts, with the Dual LC condition showing the greatest average RT. However, the confidence intervals indicate substantial overlap among the conditions, suggesting that while there are differences in average RTs, they may not reach statistical significance. This would be further verified in the pairwise analysis.

*Pairwise analysis- Language context*

A pairwise contrast analysis was performed to investigate the differences in RT among the three language contexts groups. The analysis aimed to assess whether the average RTs differ significantly between these conditions.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | 18.55 | 34.2 | 141 | 0.54 | .85 |
| ***Dense - Single*** | -9.79 | 30.9 | 132 | -0.32 | .95 |
| ***Dual - Single*** | 8.75 | 30.6 | 139 | 0.29 | .96 |

*Table 6.5.4: Pair-wise analysis based on Language context in Stroop task performance.*

The comparison between the Dual LC and Dense CSC groups yielded an estimate of 18.55 *ms* (SE = 34.2, df = 141, t = 0.54), with $p$ = .85, where performance by Dense CSC group was faster than Dual LC group, however, the difference in RT between these two conditions was not statistically significant. When comparing Dense CSC group and Single LC group where performance of Dense CSC group was faster, there was an estimated difference of 9.79 *ms* (SE = 30.9, df = 132, t = -0.32), with $p$ = .95, further indicating a lack of significant difference in RTs between these two language contexts. The contrast between Dual LC and Single LC showed a faster performance by

Single LC group, resulting in an estimate of 8.75 *ms* (SE = 30.6, df = 139, t = 0.29), with $p = .96$, suggesting that there again was no statistically significant difference in RTs between these two conditions.

Overall, the pairwise contrasts revealed no significant differences in reaction times across the three language contexts. These findings suggest that while there are slight variations in average reaction times among the conditions, they do not reach statistical significance, indicating that the language context does not substantially affect performance of the participants.

*EM Means- Task condition*

The analysis focused on determining the average RTs when participants responded to stimuli that were semantically aligned (Congruent) versus those that presented a semantic conflict (Incongruent).

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Congruent*** | 713 | 24.2 | 6.03 | 654 | 772 |
| ***Incongruent*** | 774 | 24.1 | 5.97 | 715 | 833 |

*Table 6.5.5: Group-wise EM Means based on task condition in Stroop task performance.*

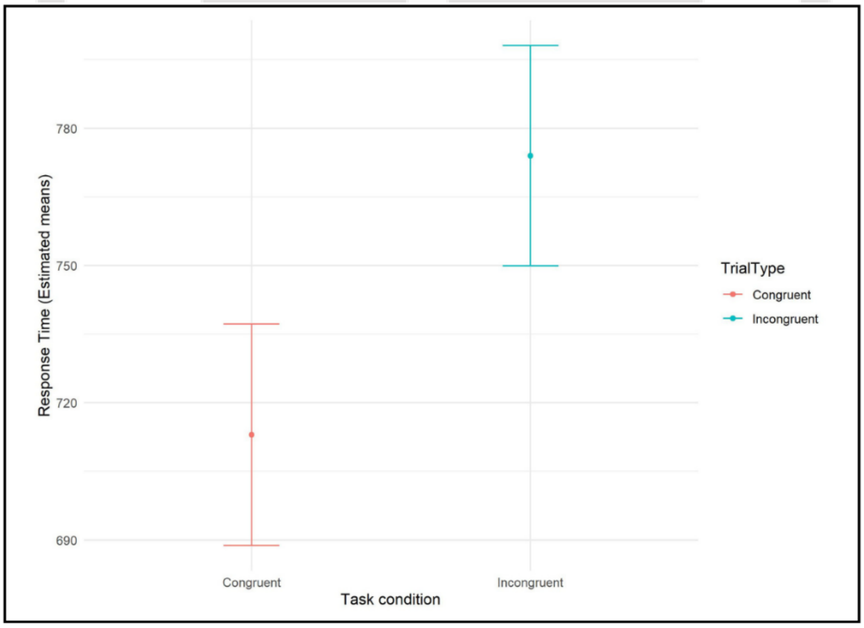


*Figure 6.5.3: Group-wise EM Means performance based on task condition in Stroop task performance. Performance in Congruent task condition was the faster than in Incongruent task condition. Bars represent 95% confidence intervals.*

The results indicated that in the Congruent task condition, the participants had an average RT of 713 *ms* (SE = 24.2, df = 6.03, 95% CI [654, 772]), suggesting that participants responded relatively quickly when the colour of the word matched the semantic meaning of the word.

On the other hand, the Incongruent condition had a greater average RT of 774 *ms* (SE = 24.1, df = 5.97, 95% CI [715, 833]), indicating that participants might require a longer response time to process information where the colour of the word did not match its semantic meaning.

The difference in average RTs between the Congruent and Incongruent conditions underscores the Stroop effect, where conflicting information leads to increased cognitive processing time. The confidence intervals for both conditions indicate that while there is substantial overlap, the difference in mean RTs highlight the greater challenge of responding in the Incongruent condition.

*Pairwise analysis- Task condition*

A pairwise contrast analysis was performed to evaluate the difference in reaction times (RT) between the Congruent and Incongruent conditions in the Stroop task. The results indicated a significant contrast between the Congruent and Incongruent conditions, with an estimated difference of 60.5 *ms* (SE = 3.19, df = 9971, t = -18.97), with $p < .0001$, highlighting a statistically significant difference in RTs, with participants responding significantly faster in the Congruent condition compared to the Incongruent condition.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Congruent - Incongruent*** | -60.5 | 3.19 | 9971 | -18.97 | < *.0001* |

*Table 6.5.6: Pair-wise analysis based on task condition in Stroop task performance.*

Thus, the pairwise contrast analysis reveals a highly significant difference in reaction times between the Congruent and Incongruent conditions, illustrating the impact of cognitive interference on performance in the Stroop task. This analysis reinforces the notion that congruency in stimuli facilitates faster processing and response times, while incongruency significantly hinders performance.

*EM Means- LC x Task condition*

An EM Means analysis was conducted to examine the interaction between language context (LC) and task condition (Congruent vs. Incongruent) on reaction times (RT) in Stroop task.

| LC | Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Congruent*** | 711 | 28.0 | 10.6 | 649 | 772 |
| ***Single*** | ***Incongruent*** | 777 | 27.8 | 10.4 | 716 | 839 |
| ***Dual*** | ***Congruent*** | 722 | 31.6 | 17.0 | 655 | 789 |
| ***Dual*** | ***Incongruent*** | 783 | 31.5 | 16.7 | 717 | 850 |
| ***Dense*** | ***Congruent*** | 707 | 31.8 | 17.4 | 640 | 775 |
| ***Dense*** | ***Incongruent*** | 761 | 31.7 | 17.2 | 694 | 828 |

*Table 6.5.7: Group-wise EM Means based on interaction between LC and task condition in overall performance in Stroop task performance.*

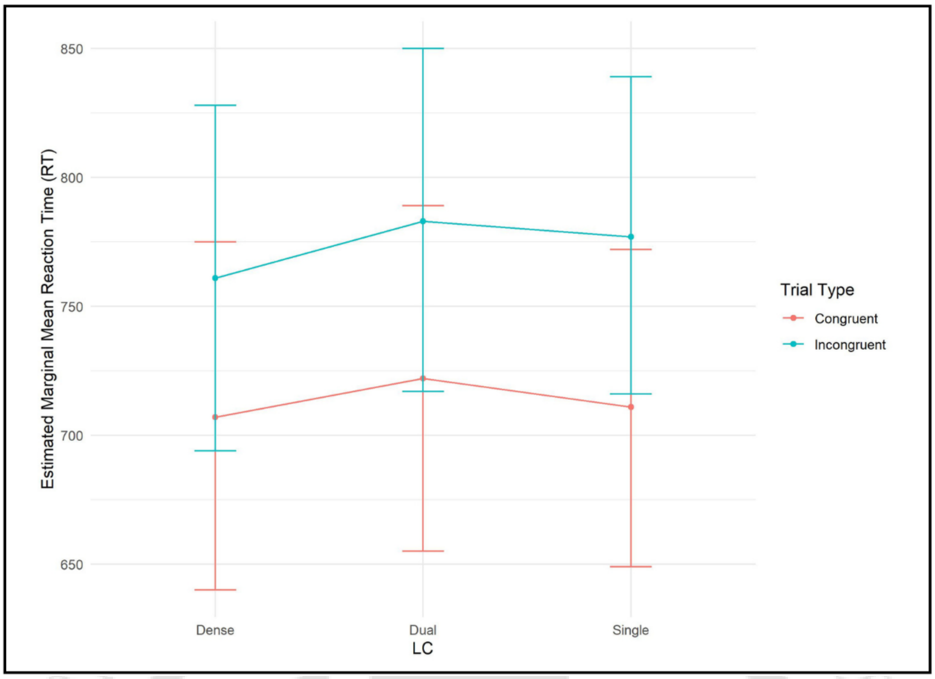


*Figure 6.5.4: Interaction of LC x Task condition in Stroop task performance.*

In Congruent task condition, Dense CSC group showed the fastest performance, with an average mean of 707 *ms* (SE = 31.8, df = 17.4, 95% CI [640, 775]). Single LC group came next, with an average of 711 *ms* (SE = 28.0, df = 10.6, 95% CI [649, 772]). Finally, Dual LC group showed highest mean RT of 722 *ms* (SE = 31.6, df = 17.0, 95% CI [655, 789]).

In Incongruent task condition, Dense CSC group had the fastest performance, with an estimated mean of 761 *ms* (SE = 31.7, df = 17.2, 95% CI [694, 828]). Single LC group followed close behind with an estimated mean of 777 *ms* (SE = 27.8, df = 10.4, 95% CI [716, 839]). Finally, Dual LC group had an estimated mean of 783 *ms* (SE = 31.5, df = 16.7, 95% CI [717, 850]).

Overall, the three groups showed faster performance in the Congruent as opposed to performance in Incongruent task condition. In both task conditions, Dense CSC group had fastest performance, and Dual LC group came last among the three LC groups.

### *Accuracy analysis*

*Error rate.* The error-rate analysis revealed that Dual LC group had the least amount of errors (2.07%), followed by Dense CSC group (2.75%) and then Single LC group (3.56%).

*GLMM.* An error analysis was conducted using a generalized linear mixed model (GLMM) to assess the effects of LC, task condition, and response time (RT) on error rates in a Stroop task. The model included random intercepts for Subject, Stimulus, and Colour. Variance components indicated that the majority of the variability in error rates was due to differences between subjects

(Variance = 0.97, SD = 0.98), while minimal variability was attributable to stimuli (Variance < 0.00, SD < 0.00) and colour (Variance = 0.16, SD = 0.40).

For the main effect of LC, none of the main effects reached statistical significance, suggesting that language context did not independently influence error likelihood. Analysis revealed that Dense CSC group and Single LC group had lower accuracy than Dual LC group. Dense CSC group had lower accuracy than Single LC group. Task condition approached significance, with an estimate of 0.50 (SE = 0.27, z = 1.87), with $p$ = .06, indicating a trend toward higher error rates in the Incongruent condition compared to the Congruent condition, again consistent with typical Stroop interference effects.

Response time was significantly associated with error likelihood, with an estimate of -0.21 (SE = 0.07, z = −3.13), $p$ = .002. This negative relationship suggests that faster responses were associated with a higher probability of errors.

The interaction between LC and task condition showed some interactions were statistically significant. For Congruent vs Incongruent conditions, Dual LC vs. Single LC groups and Dual LC vs. Dense CSC groups interaction were non-significant. However, the DCS vs. SLC interaction was significant, with an estimated difference of 0.75 (SE = 0.29, z = 2.56), with $p$ = .01, suggesting that error rates in Dense CSC group differed from Single LC group when comparing Congruent and Incongruent conditions.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| (Intercept) | -4.63 | 0.36 | -12.88 | < *.001* |
| ***LC*** | | | | |
| DLC vs. SLC | 0.24 | 0.37 | 0.66 | .51 |
| DLC vs. DCS | 0.47 | 0.39 | 1.19 | .23 |
| DCS vs. SLC | -0.23 | 0.35 | -0.66 | .51 |
| ***Task condition*** | | | | |
| Congruent vs. Incongruent | 0.50 | 0.27 | 1.87 | *.06* |
| ***Response time*** | | | | |
| RT (scaled) | -0.21 | 0.07 | -3.13 | *.002* |
| ***LC x Condition interaction*** | | | | |
| DLC vs. SLC: Congruent vs. Incongruent | 0.31 | 0.32 | 0.96 | .34 |
| DLC vs. DCS: Congruent vs. Incongruent | -0.44 | 0.35 | -1.26 | .21 |
| DCS vs. SLC: Congruent vs. Incongruent | 0.75 | 0.29 | 2.56 | *.01* |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.97 | 0.98 |
| Stimulus | (Intercept) | < 0.00 | < 0.00 |
| Colour | (Intercept) | 0.16 | 0.40 |

*Table 6.5.8: GLMM results of error analysis of Stroop task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

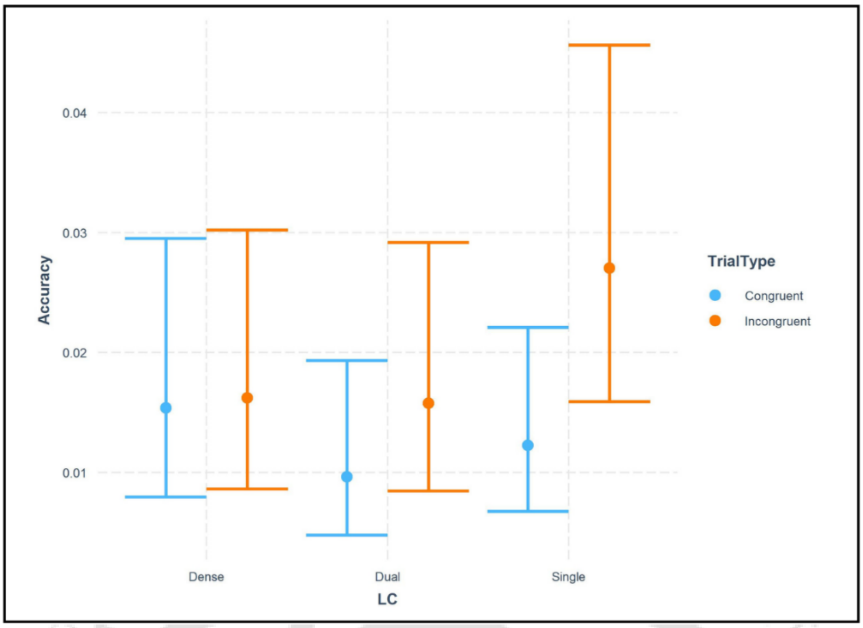


*Figure 6.5.5: Error analysis of each LC group in Stroop task performance. Each coloured bar represents a different task condition.*

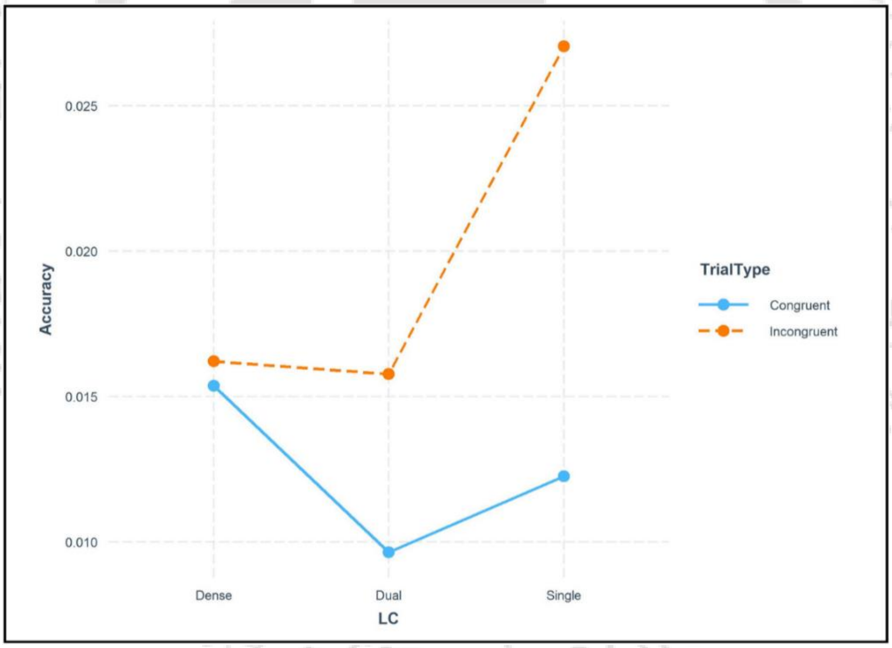


*Figure 6.5.6: Graph showing error analysis of Stroop task performance. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

To sum up, the error analysis highlights a significant association between RT and likelihood of error, with faster responses leading to more errors. While the task condition effect approached significance, indicating higher error rates in incongruent trials, language context did not independently predict errors.

*Post-error analysis*

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| (Intercept) | 739.77 | 30.03 | 14.02 | 24.63 | < *.001* |
| Post error | 138.21 | 23.84 | 132.65 | 5.80 | < *.001* |
| ***LC*** | | | | | |
| DLC vs. SLC | -25.61 | 28.65 | 102.73 | -0.89 | .37 |
| DLC vs. DCS | -31.59 | 31.85 | 102.71 | -0.99 | .32 |
| DCS vs. SLC | 5.98 | 29.23 | 102.76 | 0.20 | .84 |
| ***Task condition*** | | | | | |
| Congruent vs. Incongruent | 62.34 | 3.15 | 9922.33 | 19.76 | < *.001* |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | -48.11 | 25.98 | 69.69 | -1.85 | *.07* |
| Post error: DLC vs. DCS | -30.44 | 29.88 | 71.36 | -1.02 | .31 |
| Post error: DCS vs. SLC | -17.69 | 25.47 | 50.24 | -0.69 | .49 |
| ***Post error x Condition interaction*** | | | | | |
| Post error: Congruent vs. Incongruent | -18.04 | 18.92 | 1980.25 | -0.95 | .34 |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Correlation** |
| Subject | (Intercept) | 14941.27 | 122.23 | |
| | Post error | 1119.92 | 33.47 | 0.26 |
| Colour | (Intercept) | 1625.59 | 40.32 | |
| Stimulus | (Intercept) | 7.39 | 2.72 | |
| Residual | | 23507.77 | 153.32 | |

*Table 6.5.9: LMM results of post-error performance in Stroop task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A post-error analysis was conducted using a linear mixed model (LMM) to investigate the effects of LC, task condition, and post-error processing on RTs in a Stroop task. The model included random intercepts for Subject, Colour, and Stimulus. Random effects showed that most variability was attributable to differences between subjects (Variance = 14,941.27, SD = 122.23), while variability due to Colour (Variance = 1,625.59, SD = 40.32) and Stimulus (Variance = 7.39, SD = 2.72) was comparatively smaller. Notably, the correlation between the random intercept and the random slope for Post-Error was moderately positive (corr = 0.26), indicating that slower RTs caused greater post-error performance.

The Post-error effect was significant, with an estimate of 138.21 *ms* (SE = 23.84, t = 5.80), with *p* < .001, suggesting that RTs were significantly longer following an error, consistent with post-error slowing phenomena commonly observed in cognitive tasks.

The interaction between post-error processing and LC showed that comparisons between the groups were non-significant. The difference between Dual LC group and Single LC group approached significance, with an estimated difference of 48.11 ms (SE = 25.98, t = -1.85), with *p* = .07, suggesting a potential trend for slower post-error responses in the Single LC group compared to the Dual LC group. Dense CSC group were also shown to be slower than Dual LC group and Single LC group, but these differences were not significant.

The interaction between post-error processing and task condition was not significant, indicating that the degree of post-error slowing did not significantly differ between congruent and incongruent trials. Incongruent task condition was slower than Congruent condition.

This post-error analysis revealed significant post-error slowing, indicating that participants responded more slowly following errors, a finding consistent with existing literature on cognitive control. Task condition significantly affected RTs, with incongruent trials eliciting longer RTs than congruent trials. Although language context did not independently influence post-error RTs, the near-significant interaction between post-error processing and LC suggests that further investigation may be warranted.

## 6.6 Go/No-go task

Most tasks that measure inhibition, participants inhibit one response in favour of another. Go/No-go task, on the other hand, inhibits one's tendency to respond. It requires the participant to respond to one stimulus and refrain from responding when another stimulus appears.

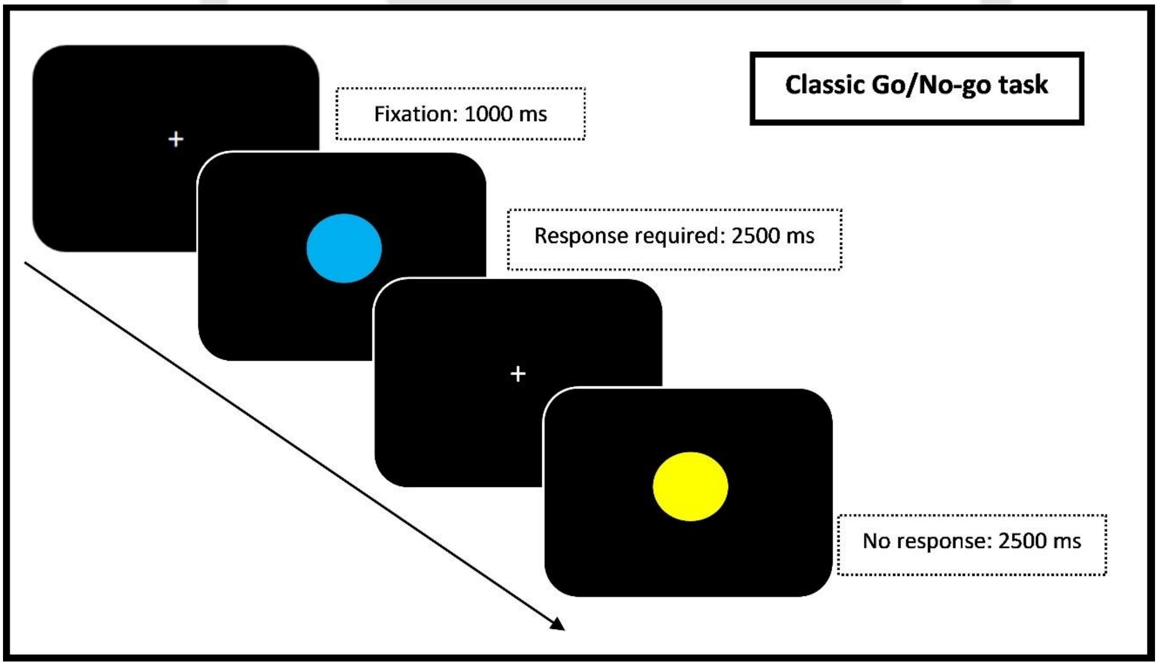


*Figure 6.6.1: Schematic diagram of Go/No-go task performed.*

### 6.6.1 Participants

The participants for this task were the same as those in previous task.

### 6.6.2 Designs and tools

The questionnaires used were the same as those used in section 6.4.2.

The task was created on E-Prime 3. There were two blocks: a practice block and a main block. The practice block had the stimulus present on the screen, with the response prompts present at the bottom of the screen. The main block consisted only of the stimulus.

### 6.6.3 Procedure

The participants answered the questionnaires and performed the task. They were presented with a stimulus- either a blue or a yellow circle. They had to respond by either pressing the space bar when presented with the 'Go' stimulus, and withhold from responding when shown the 'No-Go stimulus. The stimuli were counterbalanced across participants, where half the participants responded to the blue circle and refrained from responding to the yellow circle, and vice versa for the other half of the participants. The participants had a brief practice session followed by the main session, which consisted of 60 trials. The Go/No-go trials were 50-50 proportion, in order to make a balanced comparison between the performances in the two task conditions. A fixation cross appeared on the screen for 1500 *ms*, followed by the stimulus for 2500 *ms*. The stimulus was either a blue circle or a yellow circle. The participants had to either respond or refrain from responding to the stimulus on the screen. If the stimulus prompted a response, they had to press the spacebar.

### 6.6.4 Results

#### 6.6.4.1 Questionnaire analysis

The questionnaire analysis is the same as Section 6.5.4.1.

#### 6.6.4.2 Task analysis

Accuracy analysis was done on both, Respond and Refrain type of response, whereas RT analysis was done only on Respond response.

***RT analysis***

*Linear mixed-model analysis*

A linear mixed model was conducted to assess the impact of Language Context (LC) on reaction times across different conditions. The model included Subject as a random effect to account for individual variability, while Display and Type were included as fixed effects.

The results revealed a significant fixed effect for the intercept with an estimate of 405.44 *ms* (SE = 12.12, t = 33.44), with $p < .001$, indicating a low baseline reaction time. However, the contrasts for the Language Context conditions did not yield significant effects. Specifically, the comparison between the Single LC group and Dense CSC showed Single LC group having faster performance. Dense CSC group and Single LC group were faster than Dual LC group. These findings suggest that there were no significant differences in reaction times between the various language contexts examined in this study.

| *Fixed effects* | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 405.44 | 12.12 | 95.82 | 33.44 | < *.001* |
| ***LC*** | | | | | |
| DLC vs. SLC | -15.21 | 15.55 | 95.20 | -0.98 | .33 |
| DLC vs. DCS | -14.33 | 17.41 | 95.80 | -0.82 | .41 |
| DCS vs. SLC | -0.88 | 15.84 | 95.19 | -0.06 | .96 |

| *Random effects* | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 4163 | 64.52 |
| Display | (Intercept) | 0 | 0.00 |
| Type | (Intercept) | 0 | 0.00 |
| Residual | | 8331 | 91.28 |

*Table 6.6.1: LMM results of RT analysis of Go/No-go task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| **LC** | 8981 | 4490.5 | 2 | 95.36 | 0.54 | .59 |

*Table 6.6.2: Type III Analysis of Variance Table with Satterthwaite's method for Go/No-go task performance.*

A Type III ANOVA was conducted to examine the effect of Language Context (LC) on reaction times. The analysis revealed that the effect of LC was not statistically significant, $F(2, 95.36) = 0.54$, $p = .59$. The total sum of squares for the model was 8981, with a mean square of 4490.5. These results indicate that variations in reaction times across the different language contexts did not produce significant differences, suggesting that the grouping of the participants based on the language context did not significantly influence reaction times in this study.

### *Post-HOC analysis*

*EM Means- Language context*

Estimated marginal means (EM means) for reaction times were calculated for the three language contexts groups. Single LC group had the lowest estimated mean of 390 *ms* (SE = 10.4, df = 3.84, 95% CI [361, 420]). Dense CSC group followed closely, with an estimated average of 391 *ms* (SE = 13.1, df = 9.81, 95% CI [362, 420]). Finally, Dual LC group had the highest mean of 405 *ms* (SE = 12.2, df = 10.14, 95% CI [378, 433]).

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| **Single** | 390 | 10.4 | 3.84 | 361 | 420 |
| **Dual** | 405 | 12.2 | 10.14 | 378 | 433 |
| **Dense** | 391 | 13.1 | 9.81 | 362 | 420 |

*Table 6.6.3: Group-wise EM Means based on Language Context in Go/No-go task performance.*

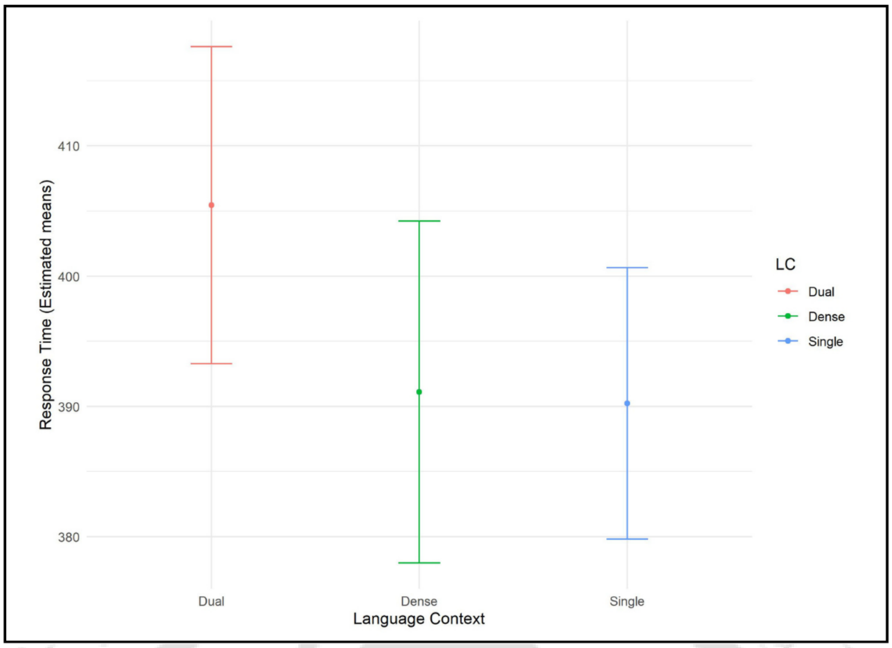


*Figure 6.6.2: Group-wise EM Means performance based on Language Context in Go/No-go task. Single LC group shows the least EM means, closely followed by Dense CSC group, and then finally the Dual LC group. Bars represent 95% confidence intervals.*

The mean performance of each LC group is not that different, and the confidence intervals for each condition overlap, indicating that these differences may not be statistically significant. Further pairwise comparisons would help determine the significance of these observed differences among the language contexts.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | 14.34 | 17.7 | 104.0 | 0.81 | .70 |
| ***Dense - Single*** | 0.88 | 17.6 | 82.8 | 0.05 | .99 |
| ***Dual - Single*** | 15.21 | 16.3 | 101.5 | 0.94 | .62 |

*Table 6.6.4: Pair-wise analysis based on Language context in Go/No-go task performance.*

*Pairwise analysis- Language context*

A pairwise comparison analysis was conducted to examine the differences in reaction times among the three language contexts: Dual, Dense, and Single. The estimate for the contrast between the Dual LC group and Dense CSC group was 14.34 *ms* (SE = 17.7, df = 104.0, t = 0.81), with $p = .70$, indicating no significant difference in reaction times between these two contexts. The contrast between the Dense CSC and Single LC groups yielded an estimate of 0.88 *ms* (SE = 17.6, df = 82.8, t = 0.05), with $p = .99$, suggesting that there was also no significant difference in reaction times between the Dense and Single contexts. Finally, the estimate for the contrast between the Dual LC and Single LC groups 15.21 *ms* (SE = 16.3, df = 101.5, t = 0.94), with $p = .62$, indicating that this comparison similarly revealed no significant difference in reaction times.

These results indicate that there were no statistically significant differences in reaction times across any of the language contexts examined in this study.

### ***Accuracy analysis***

*Error rate.* Error-rate analysis revealed that Dense CSC group had least amount of errors (0.35%), followed by Single LC group (0.75%) and the Dual LC group (0.92%).

| Error analysis | | | | |
|---|---|---|---|---|
| ***Fixed effects*** | | | | |
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -2.00 | 0.41 | -4.86 | < *.001* |
| ***LC*** | | | | |
| DLC vs. SLC | 0.22 | 0.47 | 0.48 | .63 |
| DLC vs. DCS | -0.41 | 0.61 | -0.67 | .50 |
| DCS vs. SLC | 0.64 | 0.56 | 1.14 | .25 |
| ***Response*** | | | | |
| Refrain vs. Respond | -10.64 | 1.22 | -9.69 | < *.001* |
| ***Response time*** | | | | |
| RT (scaled) | 3.49 | 0.31 | 11.38 | < *.001* |
| ***LC x Response interaction*** | | | | |
| DLC vs. SLC: Refrain vs. Respond | -1.32 | 1.24 | -1.07 | .29 |
| DLC vs. DCS: Refrain vs. Respond | -0.57 | 1.30 | -0.44 | .66 |
| DCS vs. SLC: Refrain vs. Respond | -0.75 | 1.54 | -0.49 | .63 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | < .001 | < .001 |
| Display | (Intercept) | < .001 | < .001 |

*Table 6.6.5: GLMM results of error analysis of Go/No-go task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

*GLMM.* A mixed-effects model was employed to analyse error rates in reaction times across different language contexts and response types. The model included random effects for Subject and Display, accounting for the variance among individual subjects and display types.

The random effects showed negligible variance estimates for both Subject (Variance < .001, SD < .001) and Display (Variance <.001, SD < .001), suggesting that there was minimal variability in error rates attributable to these factors.

The fixed effects analysis revealed the contrasts for Language Context group did not yield significant results. Single LC group had lower accuracy than both, Dual LC group and Dense CSC group. Dual LC group had lower accuracy than Dense CSC group.

In examining the effect of response type, a significant difference was found between Refrain and Respond, with an estimate of -10.64 (SE = 1.22, z = -9.69), $p < .001$, suggesting that participants made significantly fewer errors when refraining from responding compared to when they actively responded. Additionally, the analysis of RT (scaled) revealed a significant effect, with an estimate of 3.49 (SE = 0.31, z = 11.38), $p < .001$, indicating that faster reaction times were associated with a higher likelihood of errors. The interaction between Language Context and Response type, however, did not yield significant results.

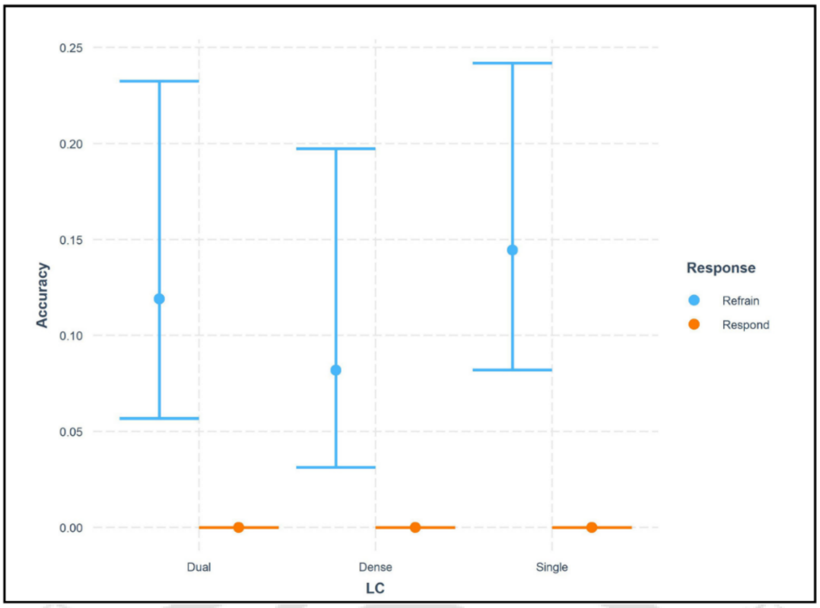


*Figure 6.6.3: Error analysis of each LC group in Go/No-go task performance. Each coloured bar represents a different task condition.*

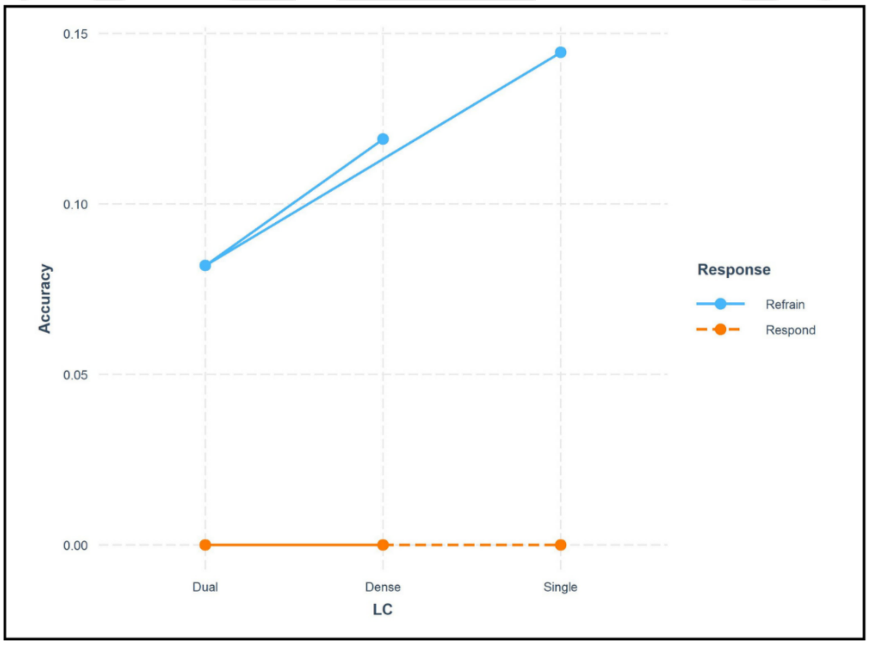


*Figure 6.6.4: Graph showing error analysis of Go/No-go task performance. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

In summary, while the analysis identified a significant effect of response type on error rates, the contrasts for Language Context did not reveal significant differences, suggesting that the manipulation of language context did not have a substantial impact on error rates in this study.

## 6.7 Discussion

The first experiment, in this set of experiments, had young adult bilinguals of a slightly wider age range (18-35) perform the Simon task. Contrary to the prediction, results showed Single LC group showing best performance, followed by Dense CSC group and finally the Dual LC group. Error-rate performance also saw Single LC group with the least errors, and Dual LC and Dense CSC groups following behind, but with minimal difference between them. Previous studies that have investigated ACH with Simon task have also found mixed results. Jylkkä and colleagues (2017, 2018) for instance, who also examined young adult bilinguals found that greater language switching experience was not associated with better inhibitory control performance. Similarly, Kheder & Kaan (2021), who examined Algerian Arabic-French young adult bilinguals, found no significant effect of code-switching frequency on RT analysis or task accuracy of Simon task.

The next experiment had young bilingual adults, 18-25 years of age, perform the Stroop task. Analysis showed that Dense CSC group performed better than the other two groups. Previous studies examining the ACH (for instance, Kałamała, Szewczyk, et al., 2020; Yang et al., 2023) using the Stroop task have not found any significant relationships between Dual LC usage and inhibitory control functioning. The performance difference among the task conditions showing statistical significance. Accuracy in performance also showed statistical significance; accuracy of performance based on task condition similarly also showed statistical significance. Accuracy-wise, there was very little difference in error rate between Dual LC group and Dense CSC group. But Single LC group had the highest error rate in this task.

Experiment 3 had participants perform the Go/No-go task. Similar to the Simon task, the participants in Single LC group had the fastest performance, however the performance difference between Single LC group and Dense CSC group was minimal. Dual LC group had the slowest performance among the three LC groups. They also had the highest error rate among the three group, whereas Dense CSC had the lowest error rate.

The results obtained with these three experiments show that the dual code-switching group did not have the predicted advantage. One way to explain this would be that when an Indian bilingual, who is often used to a heavily multilingual environment, is placed in a monolingual environment, the cognitive processes require greater exertion to keep one's language separate and not indulge in mixing between languages. So, in Single LC, the inhibitory control would be used more strongly, to continuously maintain the language, and avoid switching. This could probably explain why the Single LC group performance was better than the other language context groups in the inhibitory control performance. Thus, the context that is involved, also consists of layers, within the immediate surroundings of the participant, as well as in a larger context. This could possibly explain why Single LC group had better performance than others in Simon and Go/No-go tasks. Similarly, Dense CSC behaviour does not mean that the participant switches between the languages arbitrarily. The intra-sentential switching involves taking the competency of the other participants into consideration and changing languages as per the ability of all participants in the conversation to participate. Thus, in a multilingual environment, the language switching is not done for convenience of access for the speaker, but rather for the convenience of fellow participants in the conversation. So, a Dense CSC participant would have his languages in a state of constant activation. The act of choosing the language to use and choosing the task to perform would show similar competition within themselves for activation.

## 6.8 Chapter summary

This chapter investigated the relationship between bilingual young adults' inhibitory control performance and their contextual language usage patterns. In order to do so, three inhibitory control tasks were performed, to capture various aspects of the inhibitory control. These tasks were: Simon task for spatial interference control, Stroop task for verbal interference control, and Go/No-go for response inhibition. Participants were grouped based on their language usage patterns and their performance in each task analysed accordingly. For each task, the chapter outlines participant demographics, experimental design and tools, the methodology used, and the procedure followed. The performances were then analysed and the results discussed.

While the results produced from these tasks did not align with the premise of the Adaptive Control Hypothesis, other implications came to light that helped give better understanding of the complexity of Indian bilingual scenario.

The next chapter examines the affective control performance across bilingual young adults.

# 7 Bilingualism and Affective control

## 7.1 Introduction

Emotion and emotion control are important aspects of human mind and as such has been investigated with respect to a number of cognitive domains; for instance, risk taking and decision making (Panno et al., 2013; Shukla et al., 2019); impulsivity (Pearlstein et al., 2022); adolescent behaviour (Mueller, 2011; Poon, 2018; Schweizer et al., 2020; Steinbeis & Crone, 2016); mental health (Schweizer et al., 2019).

Yet another important cognitive domain that is relevant for studying emotion is cognitive control. The influence of emotion on the functions of cognitive control is known as Affective Control. Affective Control is the application of cognitive control to affective contexts; for example, the capacity to attend to and respond to goal-relevant information, while inhibiting attention, and responses towards distracting information (Schweizer et al., 2019). It has been observed that strong reciprocal interactions exist between the functions of cognitive control and affective control (Alguacil et al., 2013; T. Chen et al., 2016; Trafimow et al., 2004; Vermeylen et al., 2019). Studies examining the relationship between affective and cognitive control have several findings such as response to emotion words are slower as compared to neutral words (Dresler et al., 2009); words with positive valence had a greater Stroop effect than words with negative valence (Agustí et al., 2017); those with higher emotional intelligence showed greater capacity for cognitive control (Megías et al., 2017); emotional valence of words affected proactive and reactive inhibitory control (Kar et al., 2018), etc.

Studies examining the relationship between bilingualism and affective control are fairly recent. Initial studies have compared monolinguals and bilinguals and found that bilinguals were better in their affective abilities as compared to their monolingual counterparts (S. Han & Lee, 2013). Most of these studies have looked at differences in response to emotions between a bilingual's L1 and L2. Studies have found that bilinguals prefer switching between languages when expressing their emotions or recalling emotional events. Williams et al. (2020), for instance, found that negative emotional state induced more code-switching, while positive emotional state allowed for greater cognitive control, leading to lesser code-switching. Jiang et al. (2024) similarly found greater frequency of code-switching in a negative emotional state, as compared to positive emotional state.

Thus, affective control is the ability to regulate one's emotions and accordingly adapt as per the demands of the environment. It channels the executive control functions and can be considered to be a part of emotion regulation and inhibitory control mechanisms. The practice of being bilingual and maintaining one's languages, while constantly being aware of one's interactional surrounding engages one's higher order mental functions. A potential consequence of this mental exercise is that the non-linguistic general executive control also gets streamlined, leading to better executive function performances.

Therefore, this chapter looks at contextual language usage of young bilinguals and sees if this habit has any spillover effect onto their affective control performance.

## 7.2 Chapter overview

This chapter will explore the impact of contextual language usage on affective control performance of bilingual young adults. The affective control performance of the participants was investigated using emotional versions of the executive control tasks, measuring inhibitory control in presence of emotional stimuli. The two tasks used were 'hot' or emotional versions of the already used inhibitory control tasks (chapter 6): Emotional Stroop task and Emotional Go/No-go task.

## 7.3 Objective and Hypothesis

Development in affective control has been investigated through tasks that measure inhibitory control, like, in affective versus neutral contexts, typically with versions of affective Go/No-go task or emotional Stroop task (Schweizer et al., 2019). The objective of the next set of tasks, therefore, is to look at the performance of the bilinguals in the executive function of inhibition in the affective domain. The hypothesis is that the more complex the language switching context, better the affective control performance.

## 7.4 Emotional Stroop task

Like the typical Stroop Task, the Emotional Stroop task also requires the participants to ignore the words and focus on the colour of the text. The difference in this task from the classic Stroop task is that the words used here would be emotion words and neutral words, instead of colour terms. The aim was to see how the participants respond to neutral and emotion words, and if the valence of the words caused any difference in the response to them.

The words in this task were chosen based on word length, frequency of usage, and valence in case of the emotion words. The words chosen were 3-letter, 4-letter, 5-letter, and 6-letter long. Their usage frequency was taken from an open access website known as The English Lexicon Project (https://elexicon.wustl.edu/) which gives access to the lexical characteristics as well as behavioral data of 40,481 words and 40,481 non-words.

For valence of the emotion words, a survey was conducted with 20 participants (not included in the task participation) wherein they were asked to rate the words they saw on a scale of 1-7 (1- extemely negative, 4-neutral, 7- extremely positive). The top scoring words were narrowed based on their valence rate and high usage frequency. The neutral words were chosen based on their orthographic proximity to the finalized emotion words. So, for instance, if 'Joy' was a 3-letter positive emotion word chosen, a neutral word chosen was 'Toy', and so on.

A total of 25 words were taken, 14 emotional words, and 11 neutral words. The words are shown in the table below *(see Table 7.4.1)*.

| Word | Valence | Word | Valence | Word | Valence |
|---|---|---|---|---|---|
| **Sad** | Negative | **Joy** | Positive | **Toy** | Neutral |
| **Fear** | Negative | **Love** | Positive | **Sat** | Neutral |
| **Hate** | Negative | **Kind** | Positive | **Gear** | Neutral |
| **Anger** | Negative | **Cheer** | Positive | **Dove** | Neutral |
| **Panic** | Negative | **Peace** | Positive | **Fate** | Neutral |
| **Danger** | Negative | **Warmth** | Positive | **Rind** | Neutral |
| **Stress** | Negative | **Relief** | Positive | **Angle** | Neutral |
| | | | | **Clear** | Neutral |
| | | | | **Lease** | Neutral |
| | | | | **Ranger** | Neutral |
| | | | | **Recess** | Neutral |

*Table 7.4.1: Word list for Emotional Stroop task.*

Responses were collected using Chronos, a response collecting instrument. Analysis will be done to compared not just their response to neutral and emotion words, but also to compare the participants' performance between positive emotion words and negative emotion words.

### 7.4.1 Participants

The participants were the same as those in Chapter 6. 107 participants, all within the age group of 18-25 ($M_{age}$ = 19.49, SD = 1.31), and were all students of IIT-Guwahati. They were made to sit in a quiet room undisturbed and were made to perform the tasks on a laptop, with a 13.3-inch screen.

### 7.4.2 Design and tools

The two questionnaires used in this task were one, which included questions from Language Experience And Proficiency Questionnaire (LEAP-Q) (Marian et al., 2007), Language History Questionnaire (LHQ 3) (P. Li et al., 2020), from (Rodriguez-Fornells et al., 2012), and another based on *Revised Bilingual Interactional Questionnaire* from (Hartanto & Yang, 2020). These were the same as those used experiments detailed in Chapters 4, 5, and 6.

The task was created on E-Prime 3.0 and was displayed on a black background. There were two blocks: a practice block and a main block. The practice block had 'XXXX' displayed at the center in 4 different colors and the participants had to respond to the colour of the display. The main block had the neutral and emotion words displayed and the participants had to ignore the text and only respond to the colour. The text colors were: red, blue, green, and yellow *(see Figure 7.4.1 for schematic diagram)*.

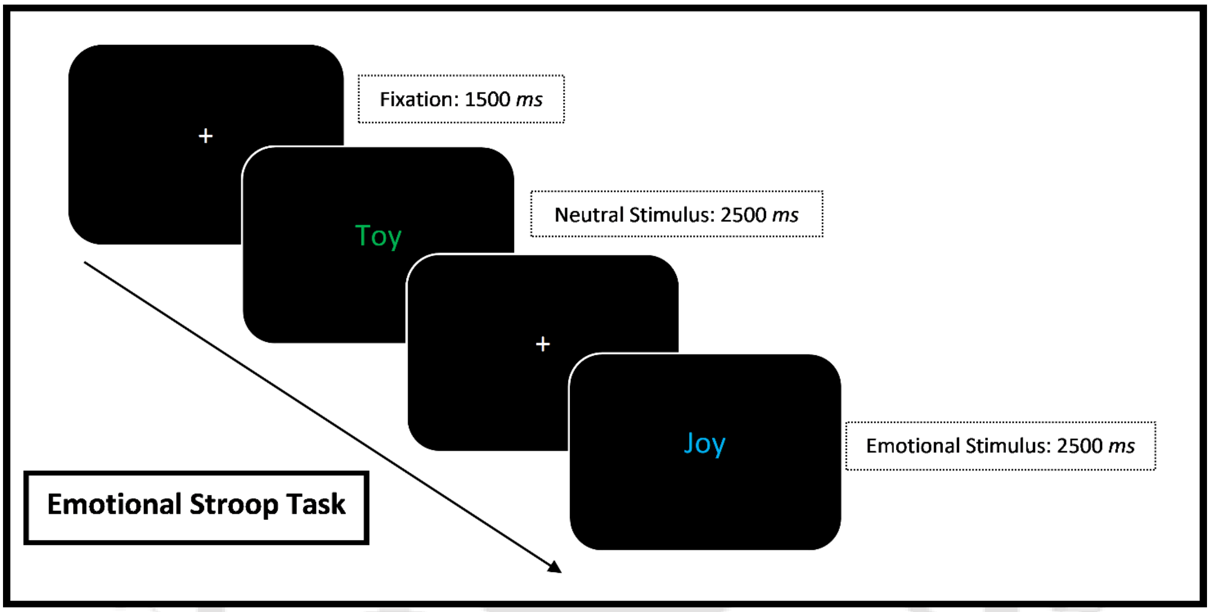


*Figure 7.4.1: Schematic diagram of Emotional Stroop task performed.*

### 7.4.3 Procedure

The participants first filled out the questionnaires, followed by the task. The experiment consisted of a practise session and a main session.

The practise session had 'XXXX' displayed at the center in 4 different colors and the participants had to respond to the colour of the display. The main session consisted of 100 trials, and had emotion words written in 4 different colors: red, blue, green, and yellow. The participants had to ignore the word and respond to the colour of the word. The response was recorded using Chronos, a response collecting instrument often used in tandem with E-Prime.

The emotion words displayed were either neutral, positive, or negative in valence. The sequence of the task consisted of a fixation cross displayed at the centre of the screen for 1500 *ms*, followed by the emotion word displayed on the screen either till a response was recorded or for 2500 *ms*, whichever occurred first. This was followed by a feedback screen displaying the time taken to respond, and if the response was correct or not. Analysis was performed on the difference in response in the different emotion words.

### 7.4.4 Results

#### 7.4.4.1 Questionnaire analysis

The questionnaire analysis was the same as Chapter 6. The 107 participants were divided as Single LC group (47 participants), Dual LC group (31 participants), and Dense Code-switching group (29 participants).

#### 7.4.4.2 Task analysis

***RT analysis***

*Linear mixed-model analysis*

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 718.22 | 28.79 | 12.60 | 24.94 | < *.001* |
| ***LC*** | | | | | |
| DLC vs. SLC | -39.88 | 26.80 | 107.84 | -1.49 | .14 |
| DLC vs. DCS | -21.93 | 29.92 | 107.82 | -0.73 | .47 |
| SLC vs. DCS | 17.95 | 27.34 | 107.70 | 0.66 | .51 |
| ***Emotion*** | | | | | |
| Neutral vs. Positive | 3.94 | 6.09 | 10225.01 | 0.65 | .52 |
| Neutral vs. Negative | -1.73 | 6.11 | 10225.96 | -0.28 | .78 |
| Positive vs. Negative | -5.67 | 6.74 | 10226.03 | -0.84 | .40 |
| ***Accuracy*** | | | | | |
| Correct vs. Error | -73.92 | 15.53 | 10241.69 | -4.76 | < *.001* |
| ***LC x Emotion interaction*** | | | | | |
| DLC vs. SLC: Neutral vs. Positive | -2.90 | 7.83 | 10225.90 | -0.37 | .71 |
| DLC vs. DCS: Neutral vs. Positive | 7.89 | 8.74 | 10225.89 | 0.90 | .37 |
| SLC vs. DCS: Neutral vs. Positive | 10.79 | 7.97 | 10230.0 | 1.36 | .18 |
| DLC vs. SLC: Neutral vs. Negative | 1.66 | 7.86 | 10225.94 | 0.21 | .83 |
| DLC vs. DCS: Neutral vs. Negative | 7.19 | 8.74 | 10225.87 | 0.82 | .41 |
| SLC vs. DCS: Neutral vs. Negative | 5.54 | 7.94 | 10230.0 | 0.70 | .49 |
| DLC vs. SLC: Positive vs. Negative | 4.56 | 8.67 | 10226.02 | 0.53 | .60 |
| DLC vs. DCS: Positive vs. Negative | -0.69 | 9.66 | 10225.93 | -0.07 | .94 |
| SLC vs. DCS: Positive vs. Negative | -5.25 | 8.813 | 10225.90 | -0.60 | .55 |
| ***LC x Task accuracy interaction*** | | | | | |
| DLC vs. SLC: Correct vs. Error | 38.21 | 20.49 | 10239.08 | 1.87 | *.06* |
| DLC vs. DCS: Correct vs. Error | 59.37 | 22.74 | 10239.37 | 2.61 | *.009* |
| SLC vs. DCS: Correct vs. Error | 21.16 | 21.33 | 10236.63 | 0.99 | .32 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Group** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 12961 | 113.85 |
| Stimulus | (Intercept) | 0 | 0.00 |
| Colour | (Intercept) | 1585 | 39.81 |
| Residual | | 18894 | 137.45 |

*Table 7.4.2: LMM analysis results of Emotional Stroop task. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed-effects model (LMM) was conducted to examine the effects of language context (LC), emotion, and task accuracy on response times. The model included random intercepts for subjects, stimuli, and colour conditions to account for individual differences and variability across features.

The random effects indicated substantial variability across subjects (Variance = 12961, SD = 113.85), with additional variance attributed to colour (Variance = 1585, SD = 39.81). No variance was found across stimuli (Variance = 0.00, SD = 0.00), suggesting minimal impact from differences between stimuli.

Int the fixed effects, for LC, no significant differences were found between the LC groups. Dual LC group had slower performance than Dense CSC group and Single LC group. Single LC group were faster than Dense CSC groups. These differences between the groups, however, were not statistically significant. For emotion of the stimulus words, no significant differences were found between the response to different emotion words. Neutral words had faster response than Positive words. Negative emotion words had faster response than Neutral words and Positive emotion words.

However, task accuracy showed a significant difference, with correct responses being significantly slower than errors with an estimate of 73.92 *ms* (SE = 15.53, t = −4.76), where $p < .001$. This is further explored in the Accuracy analysis section.

Interactions between language context and emotion were also non-significant across all comparisons, with no significant interactions found for any emotion words within any language context pairings.

However, there were significant interactions between levels of LC and task accuracy. Specifically, differences between DLC and DCS in correct versus error responses were significant, with an estimated difference of 59.37 *ms* (SE = 22.74, t = 2.61), with $p = .009$. The comparison between DLC versus SLC comparison for correct versus error responses approached significance, with an estimated difference of 38.21 *ms* (SE = 20.49, t = 1.87), with $p = .06$.

Overall, these findings highlight that task accuracy significantly influences response times, with correct responses being slower than errors. While language context and emotion did not show significant main effects or interactions, the accuracy effect differed by language context.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| ***LC*** | 27938 | 13969 | 2 | 133.8 | 0.74 | .48 |
| ***Emotion*** | 54812 | 27406 | 2 | 10226.0 | 1.45 | .23 |
| ***Accuracy*** | 415789 | 415789 | 1 | 10239.1 | 22.01 | < *.001* |
| ***LC: Emotion*** | 40490 | 10123 | 4 | 10225.9 | 0.54 | .71 |
| ***LC: Accuracy*** | 135603 | 67802 | 2 | 10238.3 | 3.59 | *.03* |

*Table 7.4.3: Type III Analysis of Variance Table with Satterthwaite's method for Emotional Stroop task performance.*

A Type III ANOVA was conducted to examine the effects of Language Context (LC), Emotion (of the task stimulus), and Accuracy, along with their interactions, on response times. The analysis revealed no significant main effect of Language Context F(2,133.8) = 0.74, with $p$ = .48, indicating that differences among the LC groups did not significantly influence the RTs. Similarly, there was no significant main effect of Emotion F(2,10226) = 1.45, with $p$ = .23, suggesting that emotion of the stimulus presented did not independently impact performance. The interaction between LC and Emotion was also not significant, F(4,10225.9) = 0.54, with $p$ = .71, implying that the combined effect of these factors had no impact on the RT.

However, there was a significant main effect of Accuracy F(1,10239.1) = 22.01, with $p < .001$, demonstrating that difference in the accuracy significantly impacted the RT of the participants, indicating that accuracy played a crucial role in determining response variability. There was significant interaction between LC and Accuracy F(2,10238.3) = 3.59, with $p$ = .03. This interaction indicates that the effect of accuracy on RT depends on the language context, more of which would be explored in the Accuracy analysis.

### *Post-HOC analysis*

*EM Means- Language context*

Estimated marginal means (EMMs) were calculated to examine the differences in response times across the three Language Context (LC) conditions: Single, Dual, and Dense. The analysis revealed that the mean response time for the Single LC had the fastest performance, with an estimated mean of 661 *ms* (SE = 26.8, df = 9.59, 95% CI [601, 721]). Dual LC group followed with an estimated mean of 682 *ms* (SE = 29.6, df = 14.02, 95% CI [619, 745]). Finally, Dense CSC group followed with the highest mean RT of 695 *ms* (SE = 30.2, df = 15.19, 95% CI [630, 759]).

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 661 | 26.8 | 9.59 | 601 | 721 |
| ***Dual*** | 682 | 29.6 | 14.02 | 619 | 745 |
| ***Dense*** | 695 | 30.2 | 15.19 | 630 | 759 |

*Table 7.4.4: Group-wise EM Means based on Language Context in Emotional Stroop task performance.*

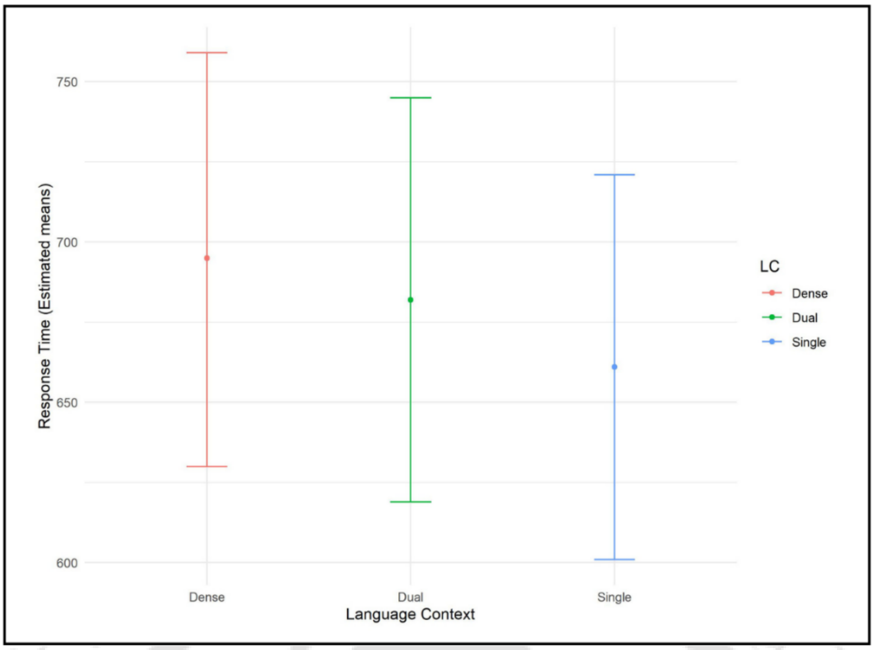


*Figure 7.4.2: Group-wise EM Means performance based on Language Context in Emotional Stroop task performance. Single LC group shows the least EM means, followed by Dual LC group, and finally the Dense CSC group. Bars represent 95% confidence intervals.*

The overlap in confidence intervals of the three LC groups suggest that these differences might not be statistically significant, which would be further explored in the pairwise analysis in the next section.

*Pairwise analysis- Language context*

A series of pairwise contrasts were conducted to compare response times between the three LC groups. The comparison between the Dual LC group and Dense CSC group revealed no significant difference, with an estimated difference of 12.8 *ms* (SE = 31.5, df = 133, t = -0.41), with $p = 0.91$. Similarly, Dense CSC group and Single LC group did not differ significantly, with an estimated difference of 34 *ms* (SE = 28.9, df = 135, t = 1.18), with $p = 0.47$. Finally, the comparison between the Dual LC and Single LC groups also showed no significant difference, with an estimated difference of 21.2 *ms* (SE = 28.3, df = 134, t = 0.75), with $p = 0.73$.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | -12.8 | 31.5 | 133 | -0.41 | .91 |
| ***Dense - Single*** | 34.0 | 28.9 | 135 | 1.18 | .47 |
| ***Dual - Single*** | 21.2 | 28.3 | 134 | 0.75 | .73 |

*Table 7.4.5: Pair-wise analysis based on Language context in Emotional Stroop task performance.*

Overall, these results indicate that response times were comparable across the Single, Dual, and Dense language contexts, with no statistically significant differences between any pair of conditions.

*EM Means- Task condition*

Estimated marginal means were calculated to examine the effect of emotion of the stimulus words on the participants' response times. The analysis indicated that the least mean RT was in the Neutral condition with an average estimate of 677 *ms* (SE = 23.3, df = 5.61, 95% CI [619, 735]). The Negative emotion task condition closely followed, with an estimated mean RT of 678 *ms* (SE = 23.4, df = 5.65, 95% CI [620, 736]). The Positive task condition had a mean RT of 683 *ms* (SE = 23.4, df = 5.65, 95% CI [624, 741]).

| Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Neutral*** | 677 | 23.3 | 5.61 | 619 | 735 |
| ***Positive*** | 683 | 23.4 | 5.65 | 624 | 741 |
| ***Negative*** | 678 | 23.4 | 5.65 | 620 | 736 |

*Table 7.4.6: Group-wise EM Means based on task condition in Emotional Stroop task performance.*

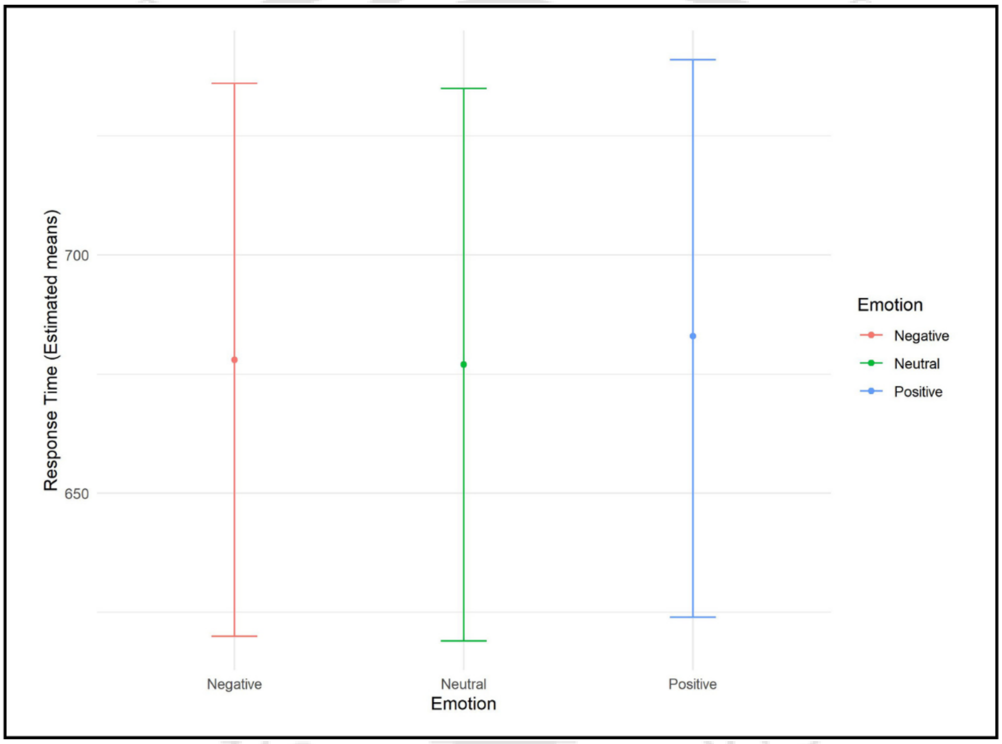


*Figure 7.4.3: Group-wise EM Means performance based on task condition in Emotional Stroop task performance. Performance in Neutral task condition was the fastest, very closely followed by Negative task condition, and Positive task condition came at the end. Bars represent 95% confidence intervals.*

Although there were slight numerical differences among the emotional conditions, the overlapping confidence intervals suggest that these differences are not statistically significant.

*Pairwise analysis- Task condition*

Pairwise contrasts were conducted to examine differences in response times between the different emotion words. The comparison between the Neutral and Positive conditions showed no significant difference, with an estimated difference of 5.60 *ms* (SE = 3.34, df = 24.1, t = -1.68), with *p* = 0.24. Similarly, Neutral and Negative conditions did not differ significantly, with an estimated difference of 1.22 *ms* (SE = 3.35, df = 24.2, t = -0.36), with *p* = 0.93. The comparison between the Negative and Positive conditions also revealed no significant difference, with an estimate of 4.38 *ms* (SE = 3.70, df = 24.2, t = -1.18), with *p* = 0.47.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Neutral – Positive*** | -5.60 | 3.34 | 24.1 | -1.68 | .24 |
| ***Neutral – Negative*** | -1.22 | 3.35 | 24.2 | -0.36 | .93 |
| ***Negative – Positive*** | -4.38 | 3.70 | 24.2 | -1.18 | .47 |

*Table 7.4.7: Pair-wise analysis based on task condition in Emotional Stroop task performance.*

In summary, these results, along with the LMM analysis, as well as EM Means analysis indicate that response times were consistent across the different emotion conditions, suggesting that the emotional context did not have a significant effect on performance of the participants.

*EM Means- LC x Task condition*

Estimated marginal means (EMMs) were calculated to evaluate the interaction between language context (LC: Single, Dual, and Dense) and emotion task conditions (Neutral, Positive, and Negative) on response times.

| LC | Condition | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Neutral*** | 660 | 26.9 | 9.75 | 600 | 721 |
| ***Single*** | ***Positive*** | 662 | 27.0 | 9.86 | 601 | 722 |
| ***Single*** | ***Negative*** | 660 | 27.0 | 9.87 | 600 | 721 |
| ***Dual*** | ***Neutral*** | 681 | 29.7 | 14.31 | 618 | 745 |
| ***Dual*** | ***Positive*** | 685 | 29.9 | 14.56 | 621 | 749 |
| ***Dual*** | ***Negative*** | 680 | 29.8 | 14.47 | 616 | 743 |
| ***Dense*** | ***Neutral*** | 689 | 30.4 | 15.48 | 624 | 754 |
| ***Dense*** | ***Positive*** | 701 | 30.5 | 15.77 | 636 | 766 |
| ***Dense*** | ***Negative*** | 694 | 30.5 | 15.73 | 630 | 759 |

*Table 7.4.8: Group-wise EM Means based on interaction between LC and task condition in Emotional Stroop task performance.*

In Neutral task condition, Single LC group had the fastest performance, with an estimated mean of 660 *ms* (SE = 26.9, df = 9,75, 95% CI [600, 721]). Dual LC group came next, with an estimated average of 681 *ms* (SE = 29.7, df = 14.31, 95% CI [618, 745]). Dense CSC group had an estimated average of 689 *ms* (SE = 30.4, df = 15.48, 95% CI [624, 754]).

In Positive task condition, Single LC group had the fastest performance, with an estimated average 662 *ms* (SE = 27.0, df = 9.86, 95% CI [601, 722]). Dual LC group had an estimated mean of 685 *ms* (SE = 29.9, df = 14.56, 95% CI [621, 749]). Dense CSC group had an estimated average of 701 *ms* (SE = 30.5, df = 15.77, 95% CI [636, 766]).

In Negative task condition, Single LC group had an estimated average of 660 *ms* (SE = 27.0, df = 9.87, 95% CI [600, 721]). Dual LC group had an average of 680 *ms* (SE = 29.8, df = 14.47, 95%

CI [616, 743]). Dense CSC group had an estimated average of 694 *ms* (SE = 30.5, df = 15.73, 95% CI [630, 759]).

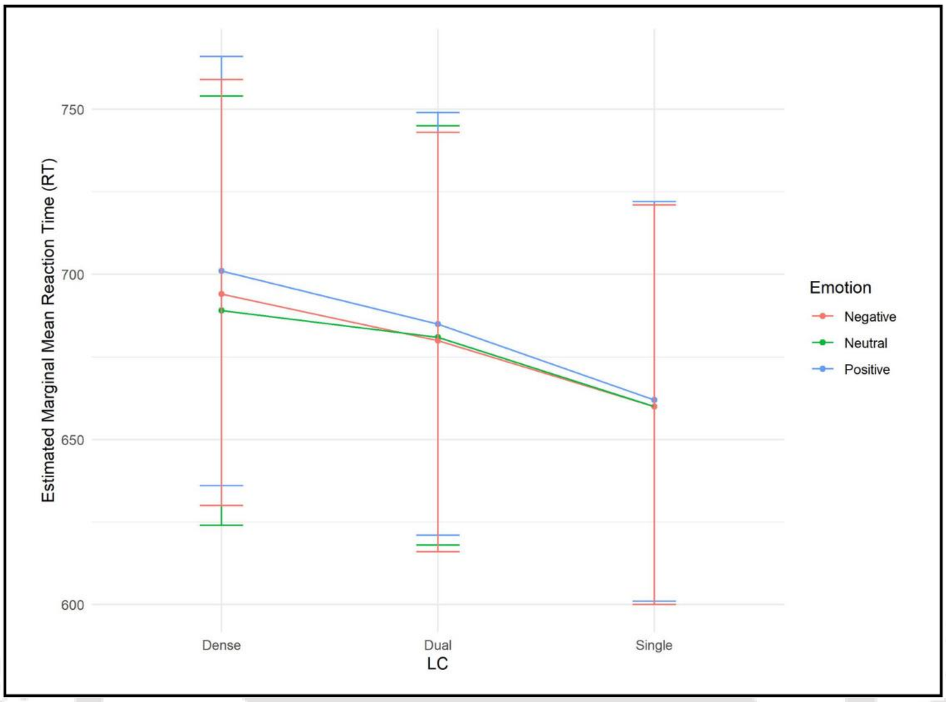


*Figure 7.4.4: Interaction of LC x Task condition in Emotional Stroop task performance.*

To summarize, Single LC group outperformed the other groups in all the three task conditions. Dense CSC group was the slowest in all task conditions. Neutral and Negative had similar means in all three LC groups, whereas Positive task condition had comparably higher means in the three LC groups.

***Accuracy analysis***

*Error rate.* The three LC groups had similar error rates. Single LC group had the least errors at 2.46%, followed by Dense CSC group with 2.59%, and then the Dual LC group with 2.86%.

*GLMM.* A generalized linear mixed-effects model (GLMM) was conducted to examine the influence of language context (LC), emotion, and response time on error rates in a Stroop task. The analysis included random intercepts for subjects and colour conditions to account for individual variability and differences across stimulus categories.

The random effects analysis revealed significant variability across subjects (Variance = 0.91, SD = 0.95), indicating individual differences in error rates. The random effect of colour of the stimulus had a variance of 0.42 (SD=0.65), suggesting some influence. However, no variance was detected across stimulus words (Variance = 0.00, SD = 0.00).

LC groups did not show statistically significant differences among each other. Dual LC group had lower accuracy than Dense CSC group and Single LC group. Dense CSC group had a lower accuracy than Single LC group. In terms of emotion of the stimulus, the difference between Neutral and Negative task conditions approached significance, with an estimated difference of 0.49 (SE = 0.25, z = 1.94), with $p = .05$, suggesting a trend where performance in Negative task condition may be associated with higher error rates. Positive emotion words and Negative emotion words had lower accuracy than Neutral emotion words, this was not statistically significant.

Response time, which was scaled for analysis, showed a significant negative effect, with an estimate of 0.47 (SE = 0.07, z = −6.45), with $p < .001$. This indicates that longer response times were associated with lower error probabilities, suggesting a trade-off between speed and accuracy.

In summary, the GLMM analysis showed that response time significantly predicted error rates, with longer response times associated with fewer errors. Although language context and emotion did not have significant main effects or interactions, there was a trend indicating that the negative emotional condition might increase error rates compared to neutral stimuli.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -4.36 | 0.42 | -10.42 | < *.001* |
| ***LC*** | | | | |
| DLC vs. DCS | -0.05 | 0.37 | -0.14 | .89 |
| DLC vs. SLC | -0.23 | 0.34 | -0.68 | .49 |
| SLC vs. DCS | 0.18 | 0.34 | 0.53 | .60 |
| ***Emotion*** | | | | |
| Neutral vs. Positive | 0.08 | 0.28 | 0.29 | .77 |
| Neutral vs. Negative | 0.49 | 0.25 | 1.94 | *.05* |
| Positive vs. Negative | 0.41 | 0.28 | 1.44 | .15 |
| ***Response time*** | | | | |
| RT (scaled) | -0.47 | 0.07 | -6.45 | < *.001* |
| ***LC x Emotion*** | | | | |
| DLC vs. SLC: Neutral vs. Positive | 0.30 | 0.36 | 0.84 | .40 |
| DLC vs. DCS: Neutral vs. Positive | 0.03 | 0.40 | 0.07 | .95 |
| SLC vs. DCS: Neutral vs. Positive | -0.33 | 0.36 | -0.90 | .37 |
| DLC vs. SLC: Neutral vs. Negative | -0.19 | 0.34 | -0.57 | .57 |
| DLC vs. DCS: Neutral vs. Negative | -0.28 | 0.37 | -0.76 | .45 |
| SLC vs. DCS: Neutral vs. Negative | -0.09 | 0.36 | -0.25 | .80 |
| DLC vs. DCS: Positive vs. Negative | -0.26 | 0.41 | -0.62 | .53 |
| DLC vs. SLC: Positive vs. Negative | -0.50 | 0.37 | -1.35 | .18 |
| SLC vs. DCS: Positive vs. Negative | 0.24 | 0.38 | 0.62 | .54 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.91 | 0.95 |
| Stimulus | (Intercept) | 0.00 | 0.00 |
| Colour | (Intercept) | 0.42 | 0.65 |

*Table 7.4.9: GLMM results of error analysis of Emotional Stroop task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

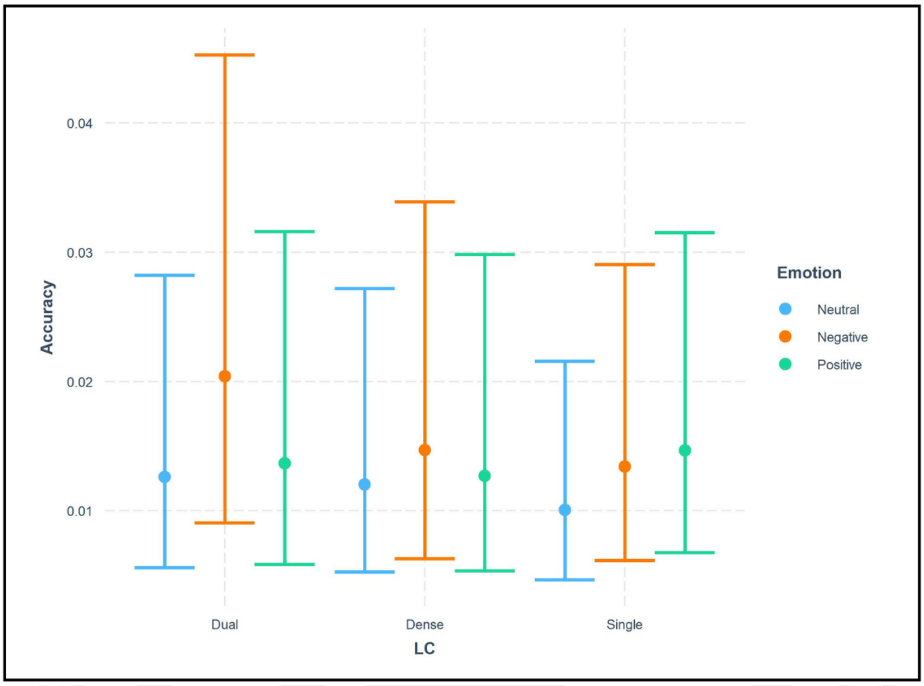


*Figure 7.4.5: Error analysis of each LC group in Emotional Stroop task performance. Each coloured bar represents a different task condition.*

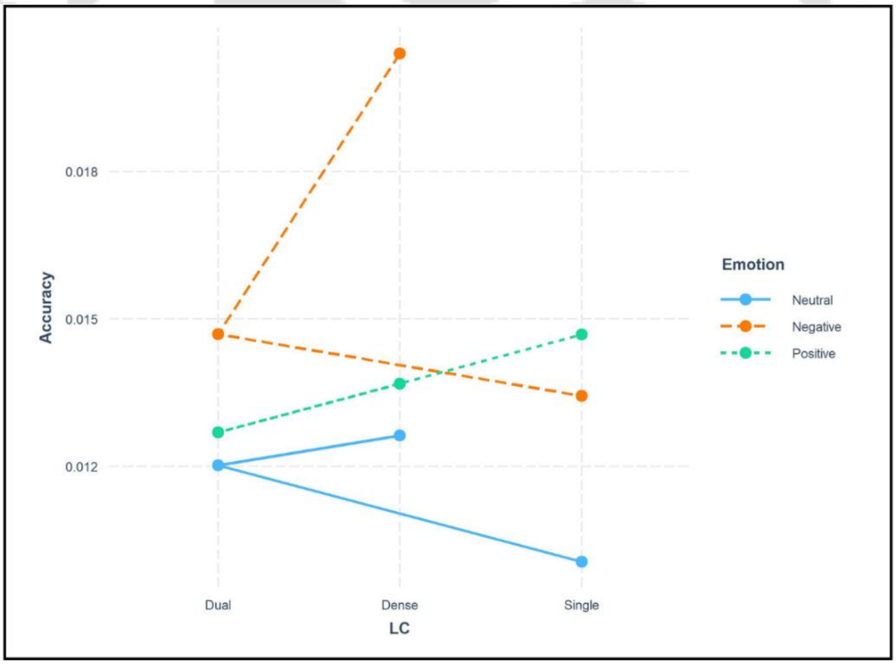


*Figure 7.4.6: Graph showing error analysis of Emotional Stroop task performance. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

### *Post-error analysis*

| ***Fixed effects*** | Est. | SE | df | t value | Pr (>\|t\|) |
|---|---|---|---|---|---|
| Intercept | 713.28 | 28.94 | 12.90 | 24.65 | < *.001* |
| Post error | 75.66 | 21.66 | 84.94 | 3.49 | *.0008* |
| ***LC*** | | | | | |
| DLC vs. DCS | -16.67 | 30.16 | 103.83 | -0.55 | .58 |
| DLC vs. SLC | -29.80 | 27.01 | 103.84 | -1.47 | .14 |
| SLC vs. DCS | 23.13 | 27.57 | 103.81 | 0.84 | .40 |
| ***Task condition*** | | | | | |
| Neutral vs. Positive | 5.02 | 3.30 | 10180.15 | 1.52 | .13 |
| Neutral vs. Negative | 1.62 | 3.30 | 10180.24 | 0.49 | .62 |
| Positive vs. Negative | -3.40 | 3.65 | 10180.29 | -0.93 | .35 |
| ***Post error x LC interaction*** | | | | | |
| Post error: DLC vs. SLC | 21.99 | 24.96 | 55.78 | 0.88 | .38 |
| Post error: DLC vs. DCS | 7.26 | 27.68 | 53.58 | 0.26 | .79 |
| Post error: SLC vs. DCS | -14.74 | 25.22 | 56.69 | -0.57 | .57 |
| ***Post error x Emotion interaction*** | | | | | |
| Post error: Neutral vs. Positive | -20.58 | 20.43 | 2082.56 | -1.01 | .31 |
| Post error: Neutral vs. Negative | -27.74 | 21.76 | 2996.45 | -1.28 | .20 |
| Post error: Positive vs. Negative | -7.16 | 23.53 | 1845.88 | -0.30 | .76 |

| ***Random effects*** | | | | |
|---|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** | **Correlation** |
| Subject | (Intercept) | 13430 | 115.89 | |
| | Post Error | 2250 | 47.43 | -0.59 |
| Stimulus | (Intercept) | 0 | 0.00 | |
| Colour | (Intercept) | 1582 | 39.78 | |
| Residual | | 18717 | 136.81 | |

*Table 7.4.10: LMM results of post-error performance in Emotional Stroop task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

A linear mixed-effects model (LMM) was conducted to examine the influence of post-error effects, language context (LC), task condition, and their interactions on response times. Random effects for subjects, stimuli, and colour were included to account for variability across these factors.

The analysis revealed significant variability across subjects (Variance = 13430, SD = 115.89), suggesting differences in baseline performance. Post-error variability within subjects (Variance = 2250, SD = 47.43) was negatively correlated with the intercept (r = −0.59), indicating that individuals who were faster overall tended to show smaller post-error slowing effects. Variance across colour conditions (Variance = 1582, SD = 39.78) was significant, while stimulus-level variance was effectively zero (Variance = 0.00, SD = 0.00), suggesting that individual stimuli did not contribute to variability in response times.

The post-error effect was highly significant, with an estimate of 75.66 *ms* (SE = 21.66, t = 3.49), *p* = .0008, indicating that responses following an error were significantly slower than those after correct responses.

No significant interactions were found between post-error effects and LC. Results showed that Dual LC group had slower post-error response than Single LC group and Dense CSC group.

Dense CSC group had slower post-error performance compared to Single LC group. Additionally, interactions between post-error effects and emotion conditions were also not significant. Response to Neutral stimuli were faster post-error than to Positive and Negative stimuli. Response to Negative stimuli post-error were slower than Positive stimuli.

In summary, this analysis highlights a significant post-error slowing effect but did not find significant main effects of language context or emotion, nor interactions between these factors and post-error responses.

## 7.5 Emotional Go/No-go task

Just like the classic Go/No-go, this task also had participants respond to one stimulus, and refrain from response to the other. In the Emotional Go/No-go, the stimulus would consist of emotion faces to which the participants either had to respond or refrain from response. In this experiment, for half the participants, a happy (positive) face meant respond, and sad/ angry (negative) face meant no response, and vice versa for other half of the participants.

### 7.5.1 Participants

The participants were the same as the previous task.

### 7.5.2 Design and tools

The questionnaires used in this task were the same as those used in Chapters 4 and 5.

The task was created on E-Prime 3.0 and was displayed on a black background. There were two blocks: a practice block and a main block. The practice block had cartoon pictures of the emotions displayed at the center of the screen, to which the participants had to respond or refrain, depending upon the emotion of the image displayed. The main block had either negative or positive facial expressions taken, with due permission from the authors, from the Indian Spontaneous Expressions Database, (Happy et al., 2017), a database created by IIT Kharagpur.

### 7.5.3 Procedure

The participants first filled out the questionnaires, followed by the task. The experiment consisted of a practise session and a main session.

*Figure 7.5.1: Emotion faces used for Emotional Go/No-Go practice trials.*

There were two blocks, a practice and a main block. The practice block had 10 cartoon faces, 5 showing positive emotions, 5 showing negative emotions *(see Figure 7.5.1)*. There were 10 trials in the practice block, to give the participants an idea how to perform the task. They then moved on to the main block.

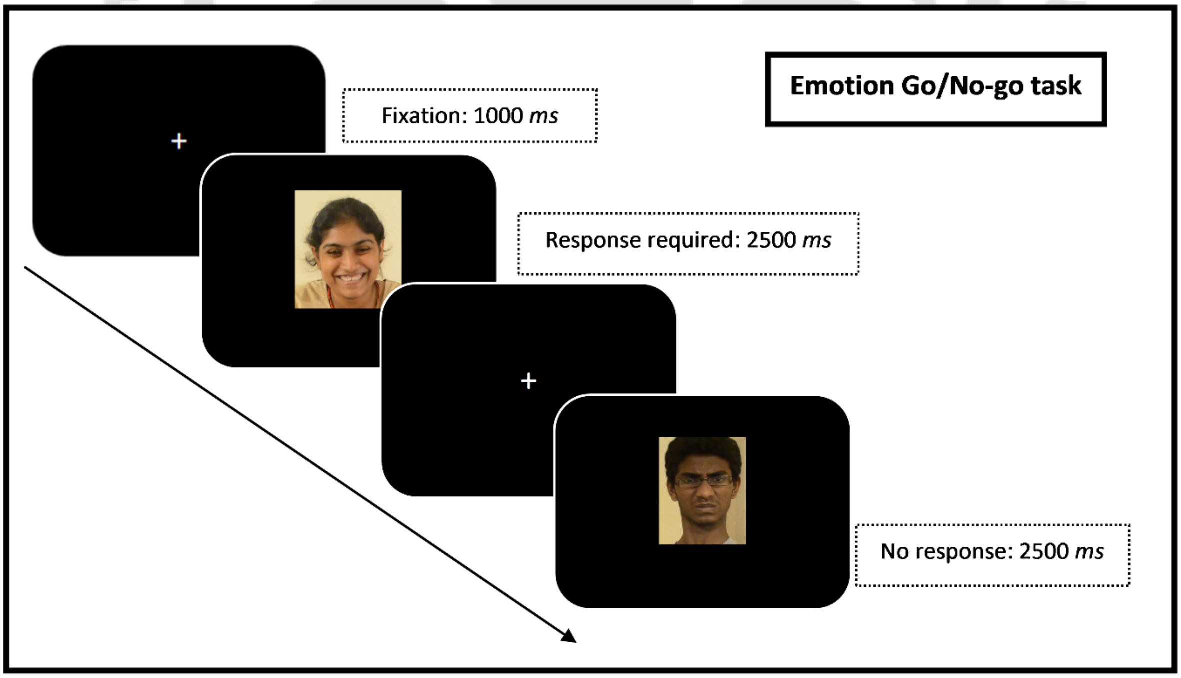


*Figure 7.5.2: Schematic diagram of Emotional Go/No-Go task.*

The main block consisted of 120 trials *(for schematic, see Figure 7.5.2)*. The participants were shown 40 emotion faces: 20 males, and 20 females. Among the males and females, there were 10 positive faces, 10 negative faces each. The participants had to press the spacebar if the image displayed was positive and refrain from responding if the image showed a negative image. This response was counterbalanced across participants.

## 7.5.4 Results

### 7.5.4.1 Questionnaire analysis

The questionnaire analysis was the same as the previous experiment.

### 7.5.4.2 Task analysis

The analysis measured their response timings, as well as their ability to refrain from response in the No-go tasks. Comparison was also made to see the performance in Go tasks, between responding to positive expressions and negative expressions.

***RT analysis***

*Linear mixed-model analysis*

| ***Fixed effects*** | | | | | |
|---|---|---|---|---|---|
| | **Est.** | **SE** | **df** | **t value** | **Pr (>\|t\|)** |
| Intercept | 571.22 | 31.06 | 305.06 | 18.39 | *< .001* |
| ***LC*** | | | | | |
| DLC vs. DCS | 2.21 | 32.42 | 101.82 | 0.07 | .95 |
| DLC vs. SLC | -38.26 | 33.24 | 101.07 | -1.15 | .25 |
| SLC vs. DCS | 40.48 | 32.32 | 100.74 | 1.25 | .21 |
| ***Emotion*** | | | | | |
| Negative vs. Positive | -22.83 | 45.05 | 276.23 | -0.51 | .61 |
| ***Gender*** | | | | | |
| Female vs. Male | 6.09 | 5.06 | 5834.99 | 1.20 | .23 |
| ***LC x Emotion interaction*** | | | | | |
| DLC vs. SLC: Negative vs. Positive | 25.27 | 45.45 | 98.88 | 0.56 | .58 |
| DLC vs. DCS: Negative vs. Positive | -54.18 | 51.25 | 98.80 | -1.06 | .29 |
| SLC vs. DCS: Negative vs. Positive | -79.45 | 47.64 | 98.55 | 1.67 | *.09* |
| ***LC x Gender interaction*** | | | | | |
| DLC vs. SLC: Female vs. Male | -2.27 | 6.47 | 5835.04 | -0.35 | .73 |
| DLC vs. DCS: Female vs. Male | 0.32 | 7.25 | 5835.13 | 0.05 | .96 |
| SLC vs. DCS: Female vs. Male | 2.59 | 6.57 | 5835.20 | 0.40 | .69 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 9079.0 | 95.28 |
| Type | (Intercept) | 409.7 | 20.24 |
| Residual | | 10770.9 | 103.78 |

*Table 7.5.1: LMM results of RT analysis of Emotional Go/No-go task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

The analysis was conducted using a linear mixed model (LMM) to examine the effects of Language Context (LC), Emotion, and Gender on the dependent variable, the response time. The random effects included intercepts for Subject (Variance = 9079.0, SD = 95.28), along with a Residual variance of 10770.9 (SD = 103.78), suggesting variability across participants and trial types.

In terms of fixed effects, for Language Context, the differences between the performances were not statistically significant. Dual LC group had faster performance than Dense CSC group. Single LC group showed faster performance than Dual LC group and Dense CSC group.

The fixed effects of Emotion and Gender also did not yield significant effects. Responses to Positive emotion faces were faster than Negative emotion faces. Responses to Female emotion faces were faster than Male emotion faces. Additionally, interactions between LC and Emotion as well as LC and Gender were examined, but neither yielded significant effects.

In conclusion, the results showed no significance of main effects or interactions for Language Context, Emotion, or Gender on the dependent variable. Further post-HOC tests were done to break down the analysis for clarity.

*ANOVA*

| | Sum Sq | Mean Sq | Num DF | Den DF | F value | Pr (>F) |
|---|---|---|---|---|---|---|
| **LC** | 16767 | 8384 | 2 | 98.7 | 0.78 | .46 |
| **Emotion** | 9420 | 9420 | 1 | 892.5 | 0.87 | .35 |
| **Gender** | 41782 | 41782 | 1 | 585.1 | 3.88 | *.05* |
| **LC: Emotion** | 30088 | 15044 | 2 | 98.7 | 1.40 | .25 |
| **LC: Gender** | 2184 | 1092 | 2 | 5835.1 | 0.10 | .90 |

*Table 7.5.2: Type III Analysis of Variance Table with Satterthwaite's method for Emotional Go/No-go task performance.*

A Type III ANOVA was conducted to examine the effects of Language Context (LC), Emotion, and Gender on RT. The results revealed that LC did not have a significant main effect, with F(2, 98.7) = 0.78 and $p$ = .46, indicating no substantial differences between the LC groups. Emotion also did not have a significant main effect, with F(1, 892.5) = 0.87, $p$ = .35, suggesting that emotion type (Negative vs. Positive) also did not influence performance.

Gender showed a significant main effect, with F(1, 585.1) = 3.88, and $p$ = .05, indicating that gender of the face displayed played a role in the speed of response of the participants. However, the interaction between LC and Emotion was not significant, with F(2, 98.7) = 1.40 and $p$ = .25, suggesting that the combined effects of LC and Emotion did not significantly affect the RT. Lastly, the interaction between LC and Gender was also non-significant, F(2, 5835.1) = 0.10 and $p$ = .90, indicating no evidence for a significant interaction between these two factors.

In summary, while the main effect of Gender approached significance, the other factors (LC, Emotion) and their interactions were not statistically significant in influencing the dependent variable.

***Post-HOC analysis***

*EM Means- Language context*

The EM Means analysis for Language Context (LC) indicated differences in the dependent variable across the three LC groups. The Single LC group showed fastest performance, with an estimated mean of 536 *ms* (SE = 20.5, df = 386, 95% CI [496, 576]). They were closely followed by the Dense CSC group with an estimated mean of 538 *ms* (SE = 23.6, df = 251, 95% CI [492, 585]). Finally came the Dual LC group, with the highest EM mean of 563 *ms* (SE = 22.5, df = 251, 95% CI [492, 585]).

| LC | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Single*** | 536 | 20.5 | 386 | 496 | 576 |
| ***Dual*** | 563 | 22.5 | 284 | 519 | 607 |
| ***Dense*** | 538 | 23.6 | 251 | 492 | 585 |

*Table 7.5.3: Group-wise EM Means based on Language Context in Emotional Go/No-go task performance.*

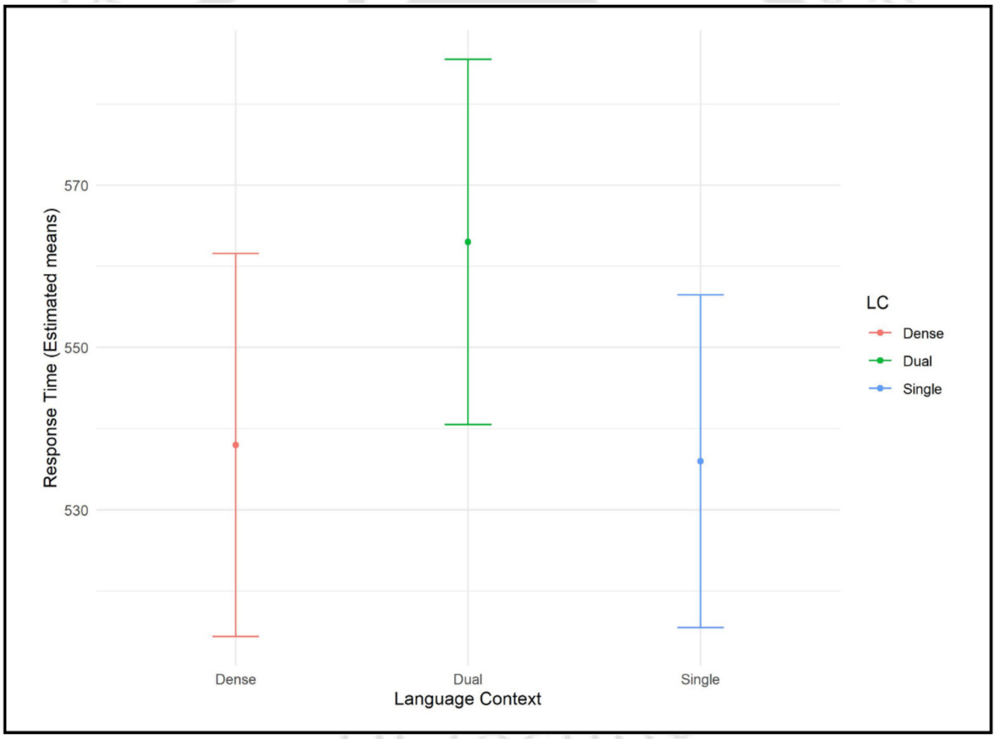


*Figure 7.5.3: Group-wise EM Means performance based on Language Context in Emotional Go/No-go task performance. Single LC group shows the least EM means, closely followed by Dense CSC group, finally followed by Dual LC group. Bars represent 95% confidence intervals.*

These results suggest that Single LC group had the fastest performance, and then Dense CSC group, and finally, Dual LC group showed the slowest performance among the three groups.

*Pairwise analysis- Language context*

The pairwise comparisons for Language Context (LC) revealed no statistically significant differences between the conditions.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Dual - Dense*** | 24.71 | 25.6 | 101 | 0.96 | .60 |
| ***Dense - Single*** | 2.05 | 23.8 | 101 | 0.09 | .47 |
| ***Dual - Single*** | 26.76 | 22.7 | 101 | 1.18 | .47 |

*Table 7.5.4: Pair-wise analysis based on Language context in Emotional Go/No-go task performance.*

The contrast between Dual LC group and Dense CSC group showed Dual LC group with a higher mean RT, yielding an estimate of 24.71 *ms* (SE = 25.6, df = 101, t = 0.96), with $p$ = .60, indicating no significant difference between these two LC groups. Between Dense CSC group and Single LC group, there was an estimated difference of 2.05 *ms* (SE = 23.8, df = 101, t = 0.09), with $p$ = .47. Finally, the contrast between Dual and Single LC groups showed an estimate of 26.76 *ms* (SE = 22.7, df = 101, t = 1.18), with $p$ = .47, suggesting that there was no significant difference between the Dual and Single LC groups conditions either. Overall, these results indicate that the Dual LC, Single LC and Dense CSC groups did not significantly differ from each other in terms of the RT performance.

*EM Means- Emotion*

EM Means analysis for Emotion revealed differences between the two emotion conditions. Positive emotion condition had an estimated mean of 529 *ms* (SE = 24.9, df = 871, 95% CI [481, 578]). For Negative emotion condition, the estimated mean was 562 *ms* (SE = 24.2, df = 1120, 95% CI [514, 609]).

| Emotion | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Negative*** | 562 | 24.2 | 1120 | 514 | 609 |
| ***Positive*** | 529 | 24.9 | 871 | 481 | 578 |

*Table 7.5.5: Group-wise EM Means based on Emotion displayed in stimulus in Emotional Go/No-go task performance.*

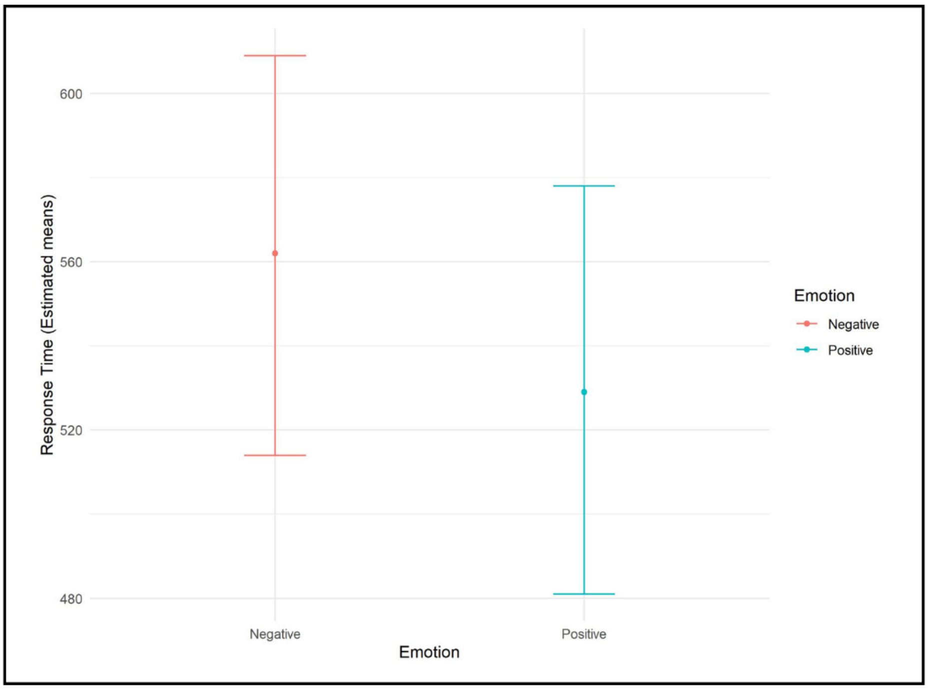


*Figure 7.5.4: Group-wise EM Means performance based on Emotion displayed in stimulus in Emotional Go/No-go task performance. Response to Positive facial expressions was faster than Negative facial expressions. Bars represent 95% confidence intervals.*

These results suggest that the Negative emotion condition had a higher estimated mean performance compared to Positive emotion condition. However, given the overlap in the confidence intervals, this difference may not be substantial.

*Pairwise analysis- Emotion*

The pairwise comparison between the Negative and Positive emotion conditions revealed no significant difference. The contrast between Negative and Positive had an estimate of 32.5 *ms* (SE = 34.7, df = 980, t = 0.94), with $p$ = 0.35, indicating that the difference between these two conditions was not statistically significant. These results suggest that there is no substantial effect of emotion type (Negative vs. Positive) on the dependent variable.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Negative – Positive*** | 32.5 | 34.7 | 980 | 0.94 | .35 |

*Table 7.5.6: Pair-wise analysis based on Emotion displayed in stimulus in Emotional Go/No-go task performance.*

*EM Means- LC x Emotion*

| LC | Emotion | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Positive*** | 537 | 26.8 | 544 | 485 | 590 |
| ***Single*** | ***Negative*** | 535 | 30.9 | 309 | 474 | 596 |
| ***Dual*** | ***Positive*** | 551 | 32.7 | 264 | 487 | 616 |
| ***Dual*** | ***Negative*** | 574 | 31.0 | 311 | 513 | 635 |
| ***Dense*** | ***Positive*** | 500 | 36.5 | 209 | 428 | 572 |
| ***Dense*** | ***Negative*** | 577 | 30.0 | 341 | 518 | 636 |

*Table 7.5.7: Group-wise EM Means based on interaction between LC and Emotion displayed in stimulus in Emotional Go/No-go task performance.*

EM Means analysis for the interaction between Language Context (LC) and Emotion revealed variations in the dependent variable across different conditions.

For the stimulus displaying positive emotion, Dense CSC group showed the fastest average performance of 500 *ms* (SE = 36.5, df = 209, 95% CI [428, 572]). They were followed by Single LC group, with an estimated average of 537 *ms* (SE = 26.8, df = 544, 95% CI [485, 590]). Finally, Dual LC group had an estimated average of 551 *ms* (SE = 32.7, df = 264, 95% CI [487, 616]).

The stimulus displaying negative emotion saw fastest performance by Single LC group with a mean estimate of 535 *ms* (SE = 30.9, df = 309, 95% CI [474, 596]). Dual LC group showed an average performance 574 *ms* (SE = 31.0, df = 311, 95% CI [513, 635]). Dense CSC group had an estimated average 577 *ms* (SE = 30.0, df = 341, 95% CI [518, 636]).

Overall, the results suggest that while the three groups showed no pattern in difference in performance in the different stimulus, Dense CSC group showed faster response to positive emotion stimuli, Single LC group showed faster performance to negative emotion stimuli. Response to negative emotion consistently produced higher estimated means than positive emotion, particularly by Dual LC and Dense CSC groups.

*EM Means- Gender*

An EM Means analysis was performed to note the estimated difference between participants reaction to the gender of the stimulus. To female stimuli, the estimated mean was 543 *ms* (SE = 17.4, df = 993, 95% CI [509, 577]). For male stimuli, the estimated mean was 548 *ms* (SE = 17.4, df = 993, 95% CI [514, 583]).

| Gender | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|
| ***Female*** | 543 | 17.4 | 993 | 509 | 577 |
| ***Male*** | 548 | 17.4 | 993 | 514 | 583 |

*Table 7.5.8: Group-wise EM Means based on Gender of the stimulus displayed in Emotional Go/No-go task performance.*

Overall, with the confidence intervals showing considerable overlap, the results suggest that there is no substantial difference between reaction to female and male stimuli.

*Pairwise analysis- Gender*

The pairwise comparison between response to Female and Male stimulus revealed a marginally significant difference. The contrast between Female and Male had an estimate of -5.44 *ms* (SE = 2.76, df = 5837, t = -1.97), with $p = 0.05$. This result suggests that there was a statistically significant difference between response to female and male stimuli, with male stimulus RT being slightly higher than female stimulus.

| Contrast | Estimate | SE | df | t ratio | *p* value |
|---|---|---|---|---|---|
| ***Female – Male*** | -5.44 | 2.76 | 5837 | -1.97 | *.05* |

*Table 7.5.9: Pair-wise analysis based on Gender of the stimulus displayed in Emotional Go/No-go task performance.*

*EM Means- LC x Gender*

EM Means analysis was conducted to examine the effect of the interaction between Language Context groups and Gender on RT.

| LC | Gender | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| ***Single*** | ***Female*** | 534 | 20.5 | 394 | 494 | 575 |
| ***Single*** | ***Male*** | 538 | 20.5 | 394 | 498 | 578 |
| ***Dual*** | ***Female*** | 560 | 22.7 | 292 | 515 | 604 |
| ***Dual*** | ***Male*** | 566 | 22.7 | 292 | 521 | 611 |
| ***Dense*** | ***Female*** | 535 | 23.8 | 257 | 488 | 582 |
| ***Dense*** | ***Male*** | 541 | 23.8 | 257 | 495 | 588 |

*Table 7.5.10: Group-wise EM Means based on interaction between LC and Gender of the stimulus displayed in stimulus in Emotional Go/No-go task performance.*

For stimulus displaying female stimulus, Single LC group showed fastest average response of 534 *ms* (SE = 20.5, df = 394, 95% CI [494, 575]). Dense CSC group came close behind with average response of 535 *ms* (SE = 23.8, df = 257, 95% CI [488, 582]). Dual LC group showed an estimated average of 560 *ms* (SE = 22.7, df = 292, 95% CI [515, 604]).

The stimulus displaying male faces had Single LC group with an estimated average response of 538 *ms* (SE = 20.5, df = 394, 95% CI [498, 578]). Dense CSC group came next with 541 *ms* (SE = 23.8, df = 257, 95% CI [495, 588]). Finally, Dual LC group had an average response of 566 *ms* (SE = 22.7, df = 292, 95% CI [521, 611]).

Overall it is observed that all three groups showed a faster response to female stimulus than to a male stimulus. Dual LC group had the highest average in both genders, and Single LC group had the lowest mean among the three groups.

*EM Means- LC x Emotion x Gender*

| LC | Gender | Emotion | EM means | SE | df | Lower CI | Upper CI |
|---|---|---|---|---|---|---|---|
| ***Single*** | ***Female*** | ***Positive*** | 535 | 26.9 | 550 | 483 | 588 |
| ***Single*** | ***Female*** | ***Negative*** | 533 | 31.0 | 311 | 472 | 594 |
| ***Single*** | ***Male*** | ***Positive*** | 539 | 26.9 | 550 | 486 | 592 |
| ***Single*** | ***Male*** | ***Negative*** | 537 | 31.0 | 311 | 476 | 598 |
| ***Dual*** | ***Female*** | ***Positive*** | 548 | 32.8 | 267 | 484 | 613 |
| ***Dual*** | ***Female*** | ***Negative*** | 571 | 31.1 | 315 | 510 | 632 |
| ***Dual*** | ***Male*** | ***Positive*** | 554 | 32.8 | 267 | 490 | 619 |
| ***Dual*** | ***Male*** | ***Negative*** | 577 | 31.1 | 315 | 516 | 638 |
| ***Dense*** | ***Female*** | ***Positive*** | 496 | 36.6 | 211 | 424 | 569 |
| ***Dense*** | ***Female*** | ***Negative*** | 573 | 30.1 | 346 | 514 | 633 |
| ***Dense*** | ***Male*** | ***Positive*** | 503 | 36.6 | 211 | 431 | 575 |
| ***Dense*** | ***Male*** | ***Negative*** | 580 | 30.1 | 346 | 521 | 639 |

*Table 7.5.11: Group-wise EM Means based on interaction between LC x Emotion x Gender of the stimulus displayed in stimulus in Emotional Go/No-go task performance.*

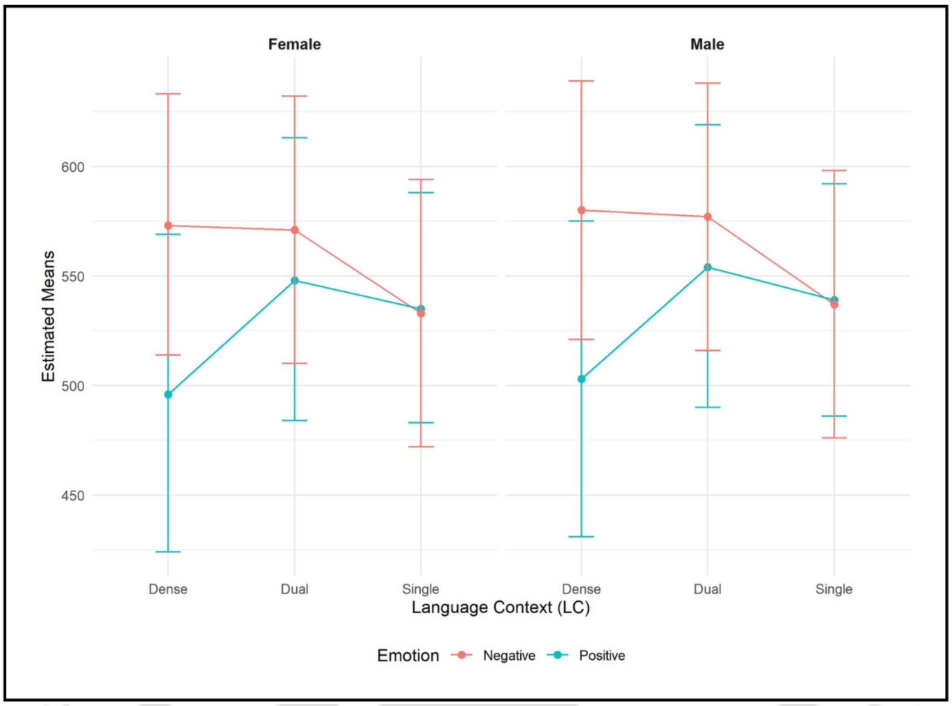


*Figure 7.5.5: Interaction of LC x Emotion x Gender of the stimulus displayed in stimulus in Emotional Go/No-go task performance.*

EM means analysis was performed to view the effect of interaction between language context, Gender and Emotion of the stimulus displayed on screen.

For display with females with positive emotions, Dense CSC group had the fastest response with an estimate of 496 *ms* (SE = 36.6, df = 211, 95% CI [424, 569]). Single LC group had an estimated average 535 *ms* (SE = 26.9, df = 550, 95% CI [483, 588]). Dual LC group showed an average of 548 *ms* (SE = 32.8, df = 267, 95% CI [484, 613]).

For display with females with negative emotions, Single LC group had an estimated mean of 533 *ms* (SE = 31.0, df = 311, 95% CI [472, 594]). Dual LC group had an estimated mean of 571 *ms* (SE = 31.1, df = 315, 95% CI [510, 632]). Dense CSC group had an estimated mean of 573 *ms* (SE = 30.1, df = 346, 95% CI [514, 633]).

For the display showing males with positive emotions, Dense CSC group had an estimated mean of 503 *ms* (SE = 36.6, df = 211, 95% CI [431, 575]). They were followed by Single LC group with an estimated average of 539 *ms* (SE = 26.9, df = 550, 95% CI [486, 592]). Dual LC group had an estimated margin of 554 *ms* (SE = 32.8, df = 267, 95% CI [490, 619]).

With the display showing males with negative emotions, Single LC group had an average estimate of 537 *ms* (SE = 31.0, df = 311, 95% CI [476, 598]). Dual LC group had an average performance of 577 *ms* (SE = 31.1, df = 315, 95% CI [516, 638]). Dense CSC group had an average response of 580 *ms* (SE = 30.1, df = 346, 95% CI [521, 639]).

Overall, these results suggest that negative emotion has generally elicited a higher average RT than positive emotions from all the three groups. Similarly, display showing males had a slower mean RT than displays with female stimulus.

### *Error analysis*

*Error-rate.* The three LC groups had similar error rates. Least errors were shown by Single LC group at 1.144%, very closely followed by Dual LC group with 1.146%, followed by Dense CSC group at 1.86%.

| ***Fixed effects*** | | | | |
|---|---|---|---|---|
| | **Est.** | **SE** | **z value** | **Pr (>\|z\|)** |
| Intercept | -2.45 | 0.45 | -5.48 | < *.001* |
| ***LC*** | | | | |
| DLC vs. DCS | 0.68 | 0.61 | 1.11 | .27 |
| DLC vs. SLC | 0.08 | 0.54 | 0.15 | .88 |
| SLC vs. DCS | 0.59 | 0.53 | 1.13 | .26 |
| ***Emotion*** | | | | |
| Negative vs. Positive | -0.14 | 0.55 | -0.25 | .80 |
| ***Gender*** | | | | |
| Female vs. Male | 0.38 | 0.49 | 0.78 | .44 |
| ***Response*** | | | | |
| Refrain vs. Respond | -7.49 | 0.62 | -12.16 | < *.001* |
| ***Response time*** | | | | |
| RT (scaled) | 2.52 | 0.13 | 18.81 | < *.001* |
| ***LC x Emotion interaction*** | | | | |
| DLC vs. SLC: Negative vs. Positive | -0.17 | 0.74 | 0.22 | .82 |
| DLC vs. DCS: Negative vs. Positive | -1.53 | 0.82 | -1.86 | *.06* |
| SLC vs. DCS: Negative vs. Positive | -1.36 | 0.79 | -1.73 | *.08* |
| ***LC x Response interaction*** | | | | |
| DLC vs. SLC: Refrain vs. Respond | -0.18 | 0.67 | -0.27 | .79 |
| DLC vs. DCS: Refrain vs. Respond | 0.79 | 0.67 | 1.18 | .24 |
| SLC vs. DCS: Refrain vs. Respond | 0.98 | 0.67 | 1.46 | .15 |
| ***LC x Gender interaction*** | | | | |
| DLC vs. SLC: Female vs. Male | -0.35 | 0.61 | -0.58 | .56 |
| DLC vs. DCS: Female vs. Male | -0.38 | 0.62 | -0.61 | .54 |
| SLC vs. DCS: Female vs. Male | -0.03 | 0.53 | -0.05 | .96 |
| ***Emotion x Gender interaction*** | | | | |
| Negative vs. Positive: Female vs. Male | -0.78 | 0.74 | -1.06 | .29 |
| ***LC x Emotion x Gender interaction*** | | | | |
| DLC vs. DCS: Negative vs. Positive: Female vs. Male | 1.14 | 0.98 | 1.16 | .25 |
| DLC vs. SLC: Negative vs. Positive: Female vs. Male | 0.79 | 0.97 | 0.82 | .41 |
| SLC vs. DCS: Negative vs. Positive: Female vs. Male | 0.34 | 0.90 | 0.38 | .70 |

| ***Random effects*** | | | |
|---|---|---|---|
| **Groups** | **Name** | **Variance** | **SD** |
| Subject | (Intercept) | 0.87 | 0.93 |

*Table 7.5.12: GLMM table of error analysis of Emotional Go/No-go task performance. (DCS: Dense code-switching; DLC: Dual-language context; SLC: Single-language context).*

*GLMM.* An error analysis was conducted using a generalized linear mixed model to assess the fixed and random effects of various factors, including language context, emotion and gender of the stimulus displayed, response type (refrain vs. respond), and response time on the likelihood of errors.

The model included random intercepts for participants, which accounted for a variance of 0.87 (SD = 0.93). This suggests that there was individual-level variation in the average measure of the dependent variable across participants, which is important for understanding how much the participants differed in their starting points.

In terms of language context, comparison between none of the levels showed any statistical significance. Dense CSC group and Single LC group showed lower accuracy than Dual LC group. Dense CSC group had lower accuracy than Single LC group. The main effects of Emotion (Negative vs. Positive) and of Gender (Female vs. Male) of the stimulus were also not statistically significant. Responses to Male emotion faces had lower accuracy than Female emotion faces. Participants' response to Negative emotion faces had lower accuracy than Positive emotion faces.

On the other hand, the fixed effect of Response Type (Refrain vs. Respond) was highly significant, with participants being much more likely to make an error when responding to the stimulus, compared to refraining from response with an estimate of 7.49 (SE = 0.62, z = -12.16), and $p < .001$. Additionally, Response Time (RT), when scaled, was a significant predictor, with shorter RTs associated with a higher likelihood of error, with an estimate of 2.52 (SE = 0.13, z = 18.81), and $p < .001$.

Most of the interactions between the fixed effect levels did not show statistical significance. In the interaction between LC and Emotion of stimulus, the comparison between Dual LC group and Dense CSC group when comparing their performance in Positive vs. Negative stimulus showed significance, having an estimate of -1.53 (SE = 0.82, z = -1.86), with $p = .06$. Similarly, comparing Single LC group with Dense CSC group, showed near statistical significance, with an estimate of -1.36 (SE = 0.79, z = -1.73), with $p = .08$.

Overall, the error analysis highlighted the significant impact of Response type and Response Time on the accuracy of the participants' response. However, neither language context, emotion, gender, nor their interactions had a significant impact on error likelihood.

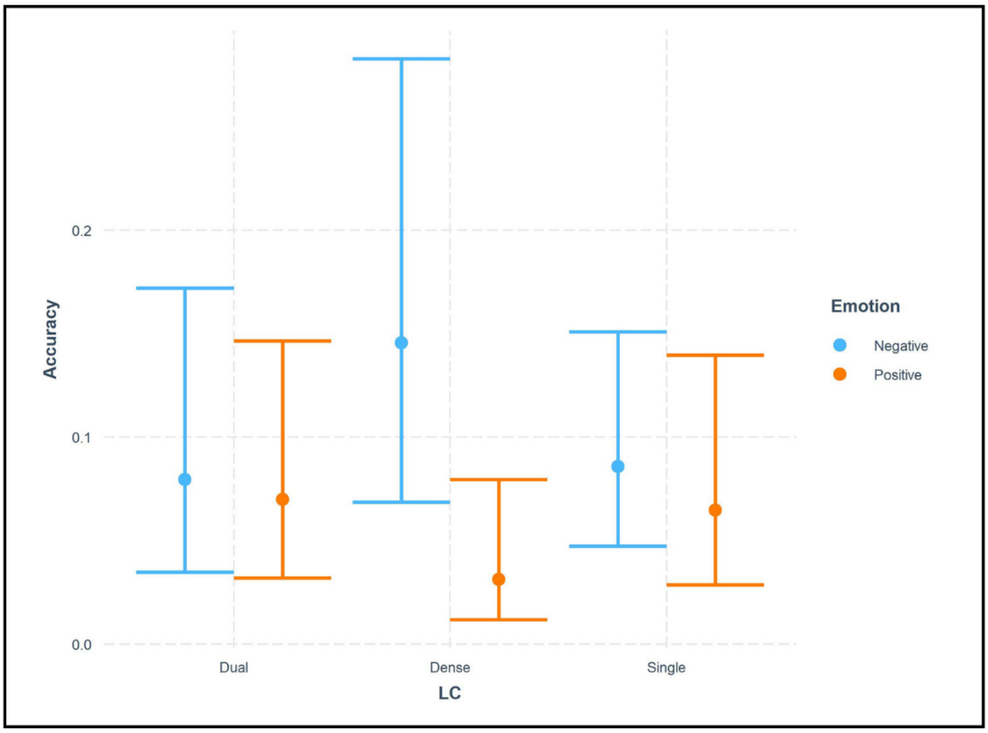


*Figure 7.5.6: Graph showing error analysis of LC x Emotion displayed in stimulus in Emotional Go/No-go task performance. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

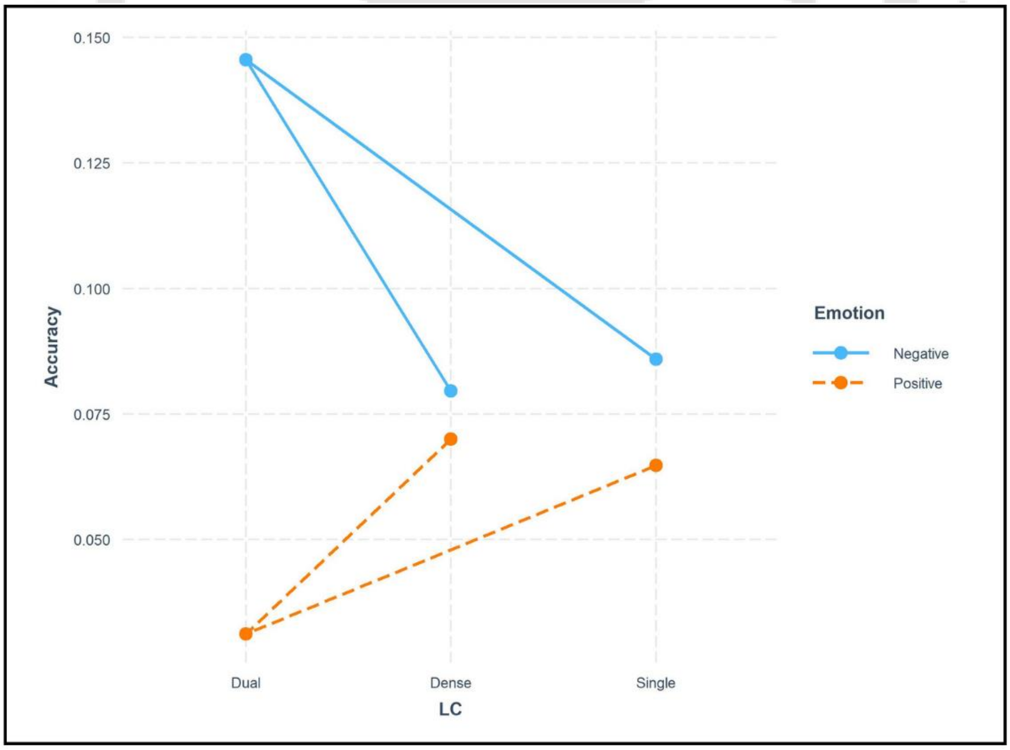


*Figure 7.5.7: Error analysis of LC x Emotion displayed in stimulus in Emotional Go/No-go task performance. The lines connect the different LC groups across the different task conditions, showing respective rates of accuracy.*

## 7.6 Discussion

The purpose of this set of experiments was to determine how a bilingual would fare in emotion regulation with respect to their contextual language switching. In order to do so, young adult bilinguals were made to perform two inhibitory control tasks, similar to the ones performed in the previous chapter, adding emotion to the stimuli. The Emotional Stroop task used emotion words, and the Emotional Go/No-go task used facial emotion images.

For Emotional Stroop task, results showed that Single LC group outperformed the other language context groups, both, in speed as well as accuracy of performance. This further emphasizes that maintaining separate linguistic environment in a heavily multilingual environment might potentially be more taxing to the inhibitory control, and its offshoots, such as the affective control, consequently leading to better performance in non-linguistic tasks.

The purpose of the emotional Stroop task is to see if valence of a word has any effect in the response of the participants. Similar to the Stroop effect, the emotional Stroop task measures the emotional Stroop effect. The emotional Stroop Effect is the difference in response to neutral words and emotion words, where response time to emotion words are longer than neutral words (Ben-Haim et al., 2016). Results showed that emotion words were, on an average, longer than neutral words, thus reflecting the Emotion Stroop Effect. Within the emotion words more specifically, positive words had longer mean average response compared to negative words.

For both, RT and error analysis, no significant relationship was found between the contextual language switching of the participants and their response to emotion and non-emotion words. This implies that the difference in language context did not play a role in the difference in response to the valence of the stimulus words. Likewise, in error analysis, a general trend of inverse relationship between speed and accuracy was found, but this was not specific to the interactional context of the bilinguals. Post-error analysis, similarly, saw responses following errors were significantly slower than those following correct responses, but the LC groups did not differ from one another in the accuracy of their performance.

Similar to the emotional Stroop task, the Emotional Go/No-go task, also saw Single LC group have the fastest performance of the three groups. However, in this task Dense CSC group closely followed Single LC group in speed, with Dual LC group bringing up the end. This is also in line with the performance of the bilinguals in the previous inhibitory control tasks in the previous chapter.

When it came to response to the stimulus, response to positive faces was faster than negative faces, and the three groups individually also showed faster performance when faced with a positive facial expression than negative. Regarding the gender of the stimulus presented, response of the three contextual groups to female faces was faster than to male faces.

Accuracy analysis saw no significant relationship among the various levels of the fixed effects, thus no significant group-wise relationship could be established. The participants made more errors when responding than when refraining from response, with longer RTs associated with higher error rate.

The results of the inhibitory control experiments in the previous chapter did not align with the ACH, with Single LC group outperforming the others in two of the three tasks performed. To further test this, the inhibitory control tasks were tweaked, adding emotion to observe the affective control performance of the bilinguals. Similar to the results of the inhibitory control tasks in the previous chapter, the tasks in this experiment did not see Dual LC group having better performance than the other groups. Rather, Single LC group outperforming the other groups in both the affective control tasks, with respect to speed as well as accuracy. This further confirms the premise that in a heavily multilingual environment, where language switching is present, the capacity to maintain separate languages for separate contexts requires a greater control than other interactional context habits. Thus, we consistently see the Single LC group outperform the others in inhibitory control performance.

## 7.7 Chapter summary

This chapter investigated the role that contextual language usage played in the performance of affective control among bilingual young adults. The affective control mechanism was assessed using two tasks: Emotional Stroop task for affective interference resolution and Emotional Go/No-go task for emotional response inhibition. Each task is structured in sections that covered participant details, task design and tools used, methodology applied and the procedure followed. This was followed by the statistical analysis and finally the results procured were discussed along with their implications. Participants were divided based on their language usage patterns and their performance in the affective control tasks were measured. Similar to the previous chapter, the findings of this chapter did not comply with the assumptions of the ACH, but rather shed new light on the complexity of the relationship between a bilingual's daily language usage and their affective control mechanism.

These implications along with the findings of the previous chapters will now be discussed in detail in the upcoming conclusion chapter.

# 8 Conclusion

## 8.1 Introduction

Bilingualism is a multifaceted phenomenon that goes beyond the simple ability to communicate in more than one language, and encompasses a dynamic relationship between cognitive functions, language processing as well as sociocultural factors. Over the years, bilingualism research has evolved from earlier models that viewed bilingualism as a cognitive burden (Saer, 1923), till the landmark study by Peal & Lambert (1962) overturned this perspective, when their study found cognitive benefits associated with being bilingual. Since then, research has continued to evolve, exploring the relationship between bilingual language use and executive control functions, with mixed results. Sanches de Oliveira & Bullock Oliveira (2022) take it a step further and claim that the research question of searching for a bilingual advantage is in itself not off to a good start because of several factors such as the dichotomous definition of being 'monolingual' and 'bilingual', not accounting for the individual differences that arise from someone's bilingual experience, and most importantly, not acknowledging how context-dependent a bilingual's language skills can be.

Even today, the volume of research on this topic has not lessened, in fact encouraging newer works to improve on previous findings, to find a more justifiable answer to the presence or absence of bilingual advantage in one's non-linguistic cognitive processes. Recent models are reaffirming the role that sociolinguistics plays in interaction with cognitive factors. For instance, in their review on the studies examining the bilingual advantage, Masullo et al. (2023) found that sociolinguistic factors involved in a bilingual's language usage experience, tend to leave a cognitive imprint, thereby influencing the 'advantage' that is seen in some bilingual studies. Their paper states that roughly 73% of the studies that have found a bilingual advantage are primarily either due to sociolinguistic factors or due to interaction between sociolinguistic and cognitive factors.

The Indian linguistic scenario is a diverse multilingual, multicultural environment, providing a compelling environment for studying bilingualism. With numerous languages spoken across different regions, and movement of the bilinguals happening towards different parts of the country for reasons such as work and education, Indian bilinguals often have to navigate complex language usage patterns in their daily communication. Their linguistic habits, therefore, exemplify how bilingualism is not just a cognitive function, but a sociocultural process that is influenced by language mode, context and interactional demands.

This thesis has attempted to look at this interaction between the cognitive and sociolinguistic factors, and the findings presented contribute to the ongoing debates about how one's bilingual experience interacts with their cognitive mechanisms. By examining the cognitive and sociocultural aspects of a bilingual's experience, this thesis has attempted to provide a more comprehensive understanding of its broader implications.

## 8.2 Findings from the Experiments

Table 8.2.1 summarizes the findings from each experiment.

| Experiment | Participants | Task | Findings |
|---|---|---|---|
| Experiment 1 (Chapter 4) | 63 young adult bilinguals; Age: 18-25 years | Bivalent Switching Task (Magnitude/Parity Task) | ▪ Dual LC group had fastest performance.<br>▪ Dual LC group had highest accuracy.*<br>▪ Dense CSC group showed fastest post-error response. |
| Experiment 2 (Chapter 4) | 61 young adult bilinguals; Age: 18-35 years | Univalent Switching Task (Number/Letter Task) | <u>Overall performance</u><br>▪ Dual LC group had the fastest performance.<br>▪ Single LC group had the highest accuracy.<br>▪ Dense CSC group had the fastest post-error performance.<br><u>Local switch cost</u><br>▪ Dual LC group had fastest performance.<br>▪ Single LC group had the highest accuracy.<br>▪ Dense CSC group had the fastest post-error performance.<br><u>Global switch cost</u><br>▪ Dual LC group had the fastest performance.<br>▪ Single LC group had the highest accuracy.<br>▪ Single LC group were fastest in their post-error performance. |
| Experiment 2 (Chapter 4) | 61 young adult bilinguals; Age: 18-35 years *(Same as above)* | Bivalent Switching Task (Colour/Shape Task) | <u>Overall performance</u><br>▪ Dual LC group showed fastest performance.<br>▪ Dual LC group had the greatest accuracy.<br>▪ Dual LC group were fastest in their post-error performance.<br><u>Local switch cost</u><br>▪ Single LC group had the fastest performance.<br>▪ Dual LC group had the greatest accuracy.<br>▪ Single LC group were fastest in their post-error performance.<br><u>Global switch cost</u><br>▪ Dual LC group had the fastest performance.* |

| | | | |
|---|---|---|---|
| | | | ▪ Dual LC group showed the greatest accuracy.<br>▪ Dual LC group were fastest in their post-error performance. |
| Experiment 3 (Chapter 5) | 61 young adult bilinguals; Age: 18-35 years *(Same as above)* | N-Back Task | ▪ Dual LC group had the fastest performance.<br>▪ Single LC group had the greatest accuracy.*<br>▪ Dual LC group were fastest in their post-error performance. |
| Experiment 4 (Chapter 6) | 61 young adult bilinguals; Age: 18-35 years *(Same as above)* | Simon Task | ▪ Single LC group had the fastest performance.*<br>▪ Single LC group had the greatest accuracy.<br>▪ Dense CSC group were fastest in their post-error performance. |
| Experiment 4 (Chapter 6) | 107 young adult bilinguals; Age: 18-25 years | Classic Stroop Task | ▪ Dense CSC group had the fastest performance.*<br>▪ Dual LC group had the greatest accuracy.<br>▪ Dual LC group were fastest in their post-error performance. |
| Experiment 4 (Chapter 6) | 107 young adult bilinguals; Age: 18-25 years *(Same as above)* | Classic Go/No-go Task | ▪ Single LC group had the fastest performance.<br>▪ Dense CSC group had the greatest accuracy. |
| Experiment 5 (Chapter 7) | 107 young adult bilinguals; Age: 18-25 years *(Same as above)* | Emotion Stroop Task | ▪ Single LC group had the fastest performance.<br>▪ Single LC group had the greatest accuracy.<br>▪ Single LC group were fastest in their post-error performance. |
| Experiment 5 (Chapter 7) | 107 young adult bilinguals; Age: 18-25 years *(Same as above)* | Emotion Go/No-go Task | ▪ Single LC group had the fastest performance.<br>▪ Dual LC group had the greatest accuracy.* |

*Table 8.2.1: Summary of findings from the experiments, including participants, tasks performed and results. (The RT analysis is summarised from the EM Means analysis, the accuracy from GLMM analysis, and post-error from LMM analysis. Those findings marked with '*' signify that different analyses showed different findings)*

The purpose of the experiments performed in this study was to see if the contextual language usage of a habitual bilingual has an influence on their non-linguistic cognitive mechanisms. In order to do so, participants were made to perform several behavioural tasks and their performances were analysed based on their language switching habits.

In Experiments 1 and 2, the performance in switching tasks was measured using 3 tasks, Bivalent Magnitude/Parity task, Univalent Number/Letter task, and Bivalent Colour/Shape task. The results showed Dual LC group aligned with the premise of the ACH, which claimed that switching between languages starts with first discontinuing from speaking the language the speaker is currently speaking in, i.e., disengaging from a task, followed by switching to speak in a new language, in other words, engaging in a new task (Green & Abutalebi, 2013). Mixed results have been obtained from studies that used switching task to examine the effects of contextual language usage. Jylkkä et al. (2017) found that the more the contextual switches reported by participants, larger was the switch cost performance. Unintentional switches led to higher error rate. On the other hand, Hartanto & Yang (2016) found that Dual LC had significantly faster performance than Single LC in switch trials, but not repeat trials, which they claimed might be due to their improved ability in dealing with task-set reconfiguration. However, there was no significant difference in accuracy of performance. Hartanto & Yang (2020) similarly found Dual LC better than Single LC at switching task performance.

Experiment 3 had the participants perform the *N*-Back task, where Dual LC group showed faster performance than other groups, while Single LC group had least errors among the three groups. The N-Back task is commonly used as a measure for working memory performance (for instance, Meule (2017), Antón et al. (2019)). According to Green & Abutalebi (2013), the cognitive process of goal maintenance requires involvement of working memory to keep updating itself to the cues at hand updating about the progress of the task performance. While this cognitive process would be needed by both, Single LC group and Dual LC group, the Dual LC group would need greater exertion of the cognitive process of goal maintenance in order to keep up with the dynamic nature of their conversational environment. A study by Jylkkä et al. (2017) had participants perform spatial *N*-Back task and found that more unintentional language switching reported, higher was the error rate. They theorised that this could be because higher unintentional language switching meant weaker cognitive control, which reflected in their working memory performance in that they had a tendency of failing to maintain specific goals of the task at hand.

Three inhibitory control tasks were performed in Experiment 4. They were Simon task, Stroop task, and Go/No-go task. Depending on the analysis, the results showed differently for RT performance of the LC groups. While LMM analysis showed Dense CSC group had fastest performance followed by Single LC group, EM Means analysis had Single LC group with the fastest performance among the three groups. In both analyses, Dual LC group was the slowest among the three groups. When Kheder & Kaan (2021) compared performance of bilinguals in Simon task based on their language proficiency and language switching practices, they found that low-proficiency frequent code-switchers became faster towards the end of the task, and that high-proficient frequent code-switchers had smaller Simon effect as they performed more trials. These results demonstrated that while frequency of language switching did play a role on the performance in Simon task, the results do not entirely concur with the premise of the Adaptive Control

Hypothesis, which hypothesized that Dual LC group would show better performance than the other groups in inhibitory control tasks.

In classic Stroop task, the LMM analysis revealed that Single LC group had the fastest performance, and as per EM Means analysis performance, Dense CSC group had the fastest performance. Dual LC group came last among the three groups in both analyses. Dual LC group did show least errors as well as fastest post-error performance among the three groups in this task. As per the ACH, Stroop task can be commonly used to measure cognitive control processes such as goal maintenance, interference suppression, and selective response inhibition. In all these processes, according to the Adaptive Control Hypothesis, due to the nature of the language usage, Dual LC speakers will exert greater demand over these control mechanisms. Other studies that examined contextual language usage and inhibitory control performance using Stroop task similarly found mixed results. Kałamała, Szewczyk, et al. (2020), for instance, found no correlation between Dual LC intensity and response inhibition performance. In their study examining the contextual language usage of older bilinguals, Yang et al. (2023) found that it was Dense CSC that had enhanced executive control performance. Thus, similar to the findings of studies using Simon task, results of bilinguals' performance in Stroop task similarly showed mixed results when it came to testing the inhibitory control performance of bilingual participants, with respect to their language switching frequency performance.

In the Go/No-go task, our analysis revealed that Single LC group had the fastest performance, whereas Dense CSC group had the greatest accuracy among the three LC groups. The Go/No-go task can be used to measure the cognitive control mechanism of salient cue detection, as well as selective response inhibition (Green & Abutalebi, 2013). X. Han et al. (2022) examined how the code-switching habits of Mandarin-English bilinguals affected their cognitive control performance and used the Go/No-go task to investigate their inhibitory control function. They found that those bilinguals with higher frequency of code-switching as well as intensive L2 use had better response inhibition, and that those bilinguals engaged in dense code-switching were more successful in withholding responses to the No-go condition of the task. These findings similarly do not align with the premise of the ACH, with LC groups other than Dual LC group outperforming in the inhibitory control performance.

Experiment 5 consisted of investigating the affective control performance of bilinguals and if their language switching behaviour had any influence on their affective control performance. Two tasks were performed: Emotional Stroop task, and Emotional Go/No-go task. Analysis of the Emotional Stroop task showed that Single LC group had the fastest responses, had greater accuracy and had fastest post-error performance as well. Analysis of the Emotional Go/No-go task showed that Single LC group had the fastest performance, whereas the accuracy performance of Dual LC group was highest among the three groups. These findings seem to be in line with what Jiang et al. (2024) which stated that those interactional contexts that exert greater demands on their cognitive control, making them more vulnerable to the effects of emotional states, therefore, interactional context like Single Language Context, which places relatively lesser demands on the cognitive control is able to outperform the other interactional context groups that have greater requirement of their executive control mechanism.

This study explored how habitual bilinguals' language switching behaviours affect their non-linguistic cognitive mechanisms, through the Adaptive Control Hypothesis. This was examined through several behavioural tasks that measured performance in cognitive mechanisms such as switching, working memory, inhibitory control and affective control. Tasks examining switching and working memory saw Dual LC group outperforming the Single LC group and Dense CSC group in *N*-Back task and switching tasks, aligning with the premise of ACH. However, tasks measuring inhibitory control performance and affective control performance showed Single LC group and Dense CSC group showing better performance than Dual LC group in both, speed and accuracy, contradicting the ACH. These findings show the complexity of the bilingual community in a non-WEIRD community like India, and the role that factors such as frequency of language switching may play in the development of non-linguistic cognitive mechanisms such as the executive control functions. The results show that the complexity of the Indian bilingual mind and their language usage might not be explained by the Adaptive Control Hypothesis and thus, requires something more complex to explain the nuances. The next section attempts to unpack these findings and explain the implications of the results.

## 8.3 Implications of the findings

This study examined the performance of the executive control mechanism of young adult bilinguals in relation with their interactional language usage habits. The results across the various tasks they performed were diverse, to say the least. This section discusses the implications of the findings mentioned above.

Firstly, contextual language usage is an important function to investigate in a non-WEIRD country like India with its extremely rich linguistic background. An average young Indian knows at least 2 languages and due to movement around the country for various reasons such as education, employment, better living opportunities, has to adapt to his environment, which includes learning its culture and language. This leads to a situation where context decides which language to use, how, and when, etc. Given that this habit of language usage is here to stay, one can question if there is any spillover effect that may help them navigate daily functioning better.

Also, when it comes to a non-WEIRD country like India, the linguistic scenario is best described along a continuum rather than in dichotomous terms. As seen from the results of the statistical analyses performed in the tasks above, comparing performances between the language context groups in showed differences between the groups but these differences were not always statistically significant. And, in some analyses, results of LMM showed one language context group performing better than the others while the EM Means analysis shows a different LC group outperforming the others. These results show that while there are some differences in the performances of the three groups, these differences are not vast. Therefore, the division based on contextual language usage also needs to reflect the nuances that go beyond the guidelines defined by the ACH.

In task switching the participants must be aware of cue activating the task to be performed, remember the tasks to be performed and respond accordingly. The constant awareness of one's environment, monitoring of the activated languages and switching between languages when required mirrors the mechanisms involved in switching between tasks. The Single-language context has separate language for separate environments, which aids in categorising the different tasks and their respective responses, thus also explaining the least errors the Single LC group had among the three groups in all variables of the univalent task. The distinct environment for each language, with no language switching taking place is mirrored in the univalent task setting, where each task performed is distinct, with no overlap in stimulus presented or their corresponding response keys. On the other hand, in a bivalent task, different tasks are performed on the same set of stimuli, which seem to mimic the dual-language context scenario, where the environment is the same, and depending on the cues the participant gets from their surroundings, the language to be spoken is chosen. This would explain the accuracy rate of the Dual LC group compared to the other groups, as well as them showing fastest performance in all variables of the bivalent task.

However, there is a possibility that the Indian bilingualism places a slightly different type of control mechanism for SLC users. The Single Language Context, as per the ACH, has well-defined environment for each language with little to no switching taking place. But for an Indian bilingual in a heavily multilingual environment, the cognitive processes require greater exertion to keep one's language separate and not indulge in mixing between languages than when in an environment that is monolingual or involving 'light' code switching. So, in Single LC, the inhibitory control would be used more strongly, to continuously maintain the language, and avoid switching. Thus, the context that is involved, also consists of layers, within the immediate surroundings of the participant, as well as in a larger context. This could possibly explain why Single LC group had better performance than others in Simon and Go/No-go tasks, that required higher degree of inhibition.

Similarly, Dense CSC behaviour does not mean that the participant switches between the languages arbitrarily. The intra-sentential switching involves taking the competence of the other participants into consideration and changing languages as per the ability of all participants in the conversation to participate. Thus, in a multilingual environment, the language switching is not done for convenience of access for the speaker, but rather for the convenience of fellow participants in the conversation. So, a Dense CSC participant would constantly have his languages in a state of constant activation. The act of choosing the language to use and choosing the task to perform would show similar competition within themselves for activation. The ACH provides an apt framework for understanding the cognitive aspects of linguistic contexts of bilinguals; however, in societies like India, and other non-WEIRD countries (for similar arguments, see X. Han et al., 2022; Hartanto & Yang, 2016; Yang et al., 2023), the layers are more nuanced and not so clear-cut. The same person can be 'participating' in different 'contexts' in different space and time. Thus, a lot of intra-personal variations might exist in these cases, affecting the outcomes in a task performance. In other words, one may need to look at the linguistic context along with socio-cultural context, rather than on its own, in order to get a clearer picture.

Secondly, another connected aspect of this three-way division is the tool for segregating the participants. This study used the questionnaire, *Revised Interactional Context Questionnaire,* by Hartanto & Yang (2020), which is also a thorough framework to capture the linguistic context. But self-report measures do have their inherent issues. In order to tap onto the underlying finer aspects of language switching pattern of a person, it might be a good idea to add some objective measures along-side the questionnaire.

Based on the above-mentioned discussion, we can attribute the mixed findings of this study to the two factors mentioned:

(a) The context: ACH defines language switching contexts into three types; however, this neat segmentation may not be entirely fit for Indian case, probably due to the underlying nuances. These nuances point towards possible interactions between switching behaviour and how the participant himself perceives it. Also, even when they do fall in one of the categories, the underlying cognitive control mechanisms might differ for Indians as the society is not just bilingual but essentially multilingual.

(b) Questionnaire: The questionnaire did not capture the groups as neatly as expected. One way to circumvent these, may be to add some extension to the contexts of ACH, with respect to cultural contexts, in order to suit the different types of scenarios across the world. In terms of finding out who would fit the categories, some new measures can probably be added to the existing questionnaires.

## 8.4 Problems and Limitations

The findings of this study may have brought new insights in the domain of bilingualism and cognitive control, there still were some limitations and problems faced in this study. For instance, this study chose not to focus on one specific bilingual language group (with fixed L1 and L2), like several studies from India have previously done (Bhandari et al., 2020; Kechu et al., 2024; Kechu & Som, 2023; Rafeekh & Mishra, 2021; J. P. Singh et al., 2019). Instead, it studied a sample of the young adult bilinguals (students), studying at a premier institution that attracts meritorious students from all over the country, in an attempt to capture the everyday diversity prevalent in the country at a given point in time. The findings of this study, however, might not be generalizable across the board, as generations differ in terms of their social and linguistic behaviour.

Being bilingual consists of multiple factors that are individualistic in nature such as language(s) proficiency, age of acquisition, as well as socio-cultural factors such as language switching, environment of language usage, effect of one's culture, etc. Each bilingual is a composite of these factors in varying degrees. A drawback of this study might be that it focuses on one specific factor of bilingualism instead of a composite study of various factors to get a more comprehensive view of the performance of bilinguals in non-linguistic factors. Studies exploring the phenomena of bilingualism in regions such as India with a rich and diverse linguistic setting are far and few in between. Investigating the bilingual advantage and the possibility of its wide-ranging reach towards other non-linguistic factors in such a setting might prove more insightful in reaching towards a definitive answer to the question of bilingual advantage.

Another key limitation is the interchangeable usage of bilingualism and multilingualism to equally define the usage of multiple languages (Koch et al., 2024; Pot et al., 2018; Titone & Tiv, 2023). There is a need for division of research that goes beyond the surface-level definition that looks at the number of languages of a speaker to define them as bilingual, trilingual, or multilingual

(Dewaele, 2021; Madrazo & Bernardo, 2020). Perhaps the complexity of their linguistic experience, which includes not just their individual experience but also their interaction with the society at large, should play a bigger role in defining the concept of being bilingual versus being multilingual.

## 8.5 Future directions

This study examined the contextual language switching habits of young adult bilinguals, where the participants were all young adult bilinguals who spoke a minimum of two languages. The results from their performance in various behavioural tasks were mixed. These results, however, do show that this line of research has a lot of untapped potential and can be further probed, probably with some changes in methodology. For instance, this study limited its participants pool to just the students of one institute, though the institute is a microcosm of India, future work can explore other such clusters of young adult bilinguals across the country and compare the results. Adding neurological aspect to the study through methodologies such as electroencephalogram (EEG), functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS) may help strengthen the findings.

Last but not the least, future work can factor in the multilingual aspect of participants, by including the number of languages as a variable. Thus, studies can have participants with knowledge of minimum 3 languages or more and adapt the questionnaires accordingly. Having well-defined multilinguals perform the same or similar tasks have the potential to shed more light on the nuances this study reports.

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# Appendices

# Appendix A

## Consent for participation

### Introduction

You are invited to take part in a research study conducted by Emily Thomas (176155102), from Centre for Linguistic Science and Technology, Indian Institute of Technology, Guwahati. Please read the following information carefully. Feel free to ask any questions before agreeing to participate.

### Purpose of the Study

The purpose of this study is to investigate how bilingualism affects cognitive performance. You will be asked to complete a questionnaire and perform some tasks. The session will last approximately 30 minutes. Your responses will be recorded and analysed for research purposes.

### Risks and Benefits

**Risks:** There are no known risks associated with participating in this study. However, if you feel uncomfortable at any point, you are free to stop.

**Benefits:** While you may not directly benefit from this study, your participation will help advance scientific understanding of the far-reaching effects of being bilingual.

### Confidentiality

Your data will be used solely for research purposes, with no identifying information linked to your responses.

### Voluntary Participation

Your participation in the study is entirely voluntary.

### Contact Information

For any queries about the study, please contact Emily Thomas (176155102), CLST, (*emily@iitg.ac.in*).

### Consent Statement

☐ I have read and understood the information provided above.

☐ I voluntarily agree to participate in this study.

**Participant's Name:**

**Participant's Signature:**

**Date:**

# Appendix B

## Participants Background Questionnaire 1

### Section A: Personal information

1. Participant ID:

2. Roll no:

3. Email ID:

4. Age group

   ☐ 18-20 years

   ☐ 21-25 years

   ☐ 26-30 years

   ☐ 31-35 years

5. Gender

   ☐ Female

   ☐ Male

   ☐ Prefer not to say

6. Handedness

   ☐ Right

   ☐ Left

   ☐ Ambidextrous (use both hands equally)

7. Any history of colour-blindness?

   ☐ Yes

   ☐ No

8. Your current educational level

   ☐ None

   ☐ Till class 5

   ☐ Till class 10

☐ Till class 12

☐ College (graduation ongoing)

☐ College (graduation complete)

☐ Post-graduation (Master's ongoing)

☐ Post-graduation (Master's complete)

☐ PhD ongoing

☐ PhD complete

9. Your mother's educational level

☐ None

☐ Till class 5

☐ Till class 10

☐ Till class 12

☐ College (graduation ongoing)

☐ College (graduation complete)

☐ Post-graduation (Master's ongoing)

☐ Post-graduation (Master's complete)

☐ PhD ongoing

☐ PhD complete

10. Your father's educational level

☐ None

☐ Till class 5

☐ Till class 10

☐ Till class 12

☐ College (graduation ongoing)

☐ College (graduation complete)

☐ Post-graduation (Master's ongoing)

☐ Post-graduation (Master's complete)

☐ PhD ongoing

☐ PhD complete

**Section B: Participant's linguistic background**

11. Your state of origin:

12. Your current region of residence:

13. Have you travelled to, and stayed in a different region within the past 6 months?

☐ Yes

☐ No

14. List out all the languages you currently know. (Even if it is a few words you picked up watching Korean dramas, or simple daily use phrases you learnt staying in a region for a long period of time). Write the languages and separate them using ';' a semi-colon.

______________________________________________

______________________________________________

______________________________________________

15. For the languages listed above, indicate if you have the skill or not (with a ✓).

| Language | Listening | Speaking | Reading | Writing |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

16. Any additional comments you would like to add?

______________________________________________

______________________________________________

______________________________________________

# Appendix C

## Participants Background Questionnaire 2

### Section A: Personal information

1. Participant ID:

2. Roll no:

3. Email ID:

4. Age group

   ☐ 18-20 years

   ☐ 21-25 years

   ☐ 26-30 years

5. Gender

   ☐ Female

   ☐ Male

   ☐ Prefer not to say

6. Handedness

   ☐ Right

   ☐ Left

   ☐ Ambidextrous (use both hands equally)

7. Any history of colour-blindness?

   ☐ Yes

   ☐ No

8. Your current educational level

   ☐ None

   ☐ Till class 5

   ☐ Till class 10

   ☐ Till class 12

☐ College (graduation ongoing)

☐ College (graduation complete)

☐ Post-graduation (Master's ongoing)

☐ Post-graduation (Master's complete)

☐ PhD ongoing

☐ PhD complete

**Section B: Participant's linguistic background**

9. Your state of origin:

10. Your current region of residence:

11. Have you travelled to, and stayed in a different region within the past 6 months?

    ☐ Yes

    ☐ No

12. List all the languages you know, in the order of how well you know the (for example, if you know English, Hindi, Kannada and for you your Kannada is strongest and Hindi is weakest, then list it as: Kannada, English, Hindi) Separate your answers with a comma (,).

    ______________________________

    ______________________________

    ______________________________

13. List all your languages in the order of when you first learned or acquired the language. Separate the answers with a comma (,)

    ______________________________

    ______________________________

    ______________________________

14. On a scale of 1-5, select the option that suits the best for the following statements (with a ✓).

| | Never | Infrequently | Occasionally | Frequently | Always |
|---|---|---|---|---|---|
| I switch between languages while | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| having a conversation | | | | | |
| I tend to mix words of one language into another while having a conversation | | | | | |
| I tend to switch between languages for entire sentences in a conversation | | | | | |
| When I switch between languages I do it deliberately | | | | | |
| I do not realise that I am switching between languages in a conversation | | | | | |
| It is difficult for me to control switching between languages in a conversation | | | | | |
| There are certain topics or issues for which I prefer switching between languages | | | | | |

**Section C: Participant Language Usage**

15. Currently, how much percentage (%) of time in a day are you exposed to each of your languages that you have mentioned? (Total should add up to 100) (Add more rows in you have more languages).

| **Language** | **Percentage of time** |
|---|---|
| | |
| **Total** | **100** |

16. When you speak to someone who is equally fluent in the same languages as you, how much percentage (%) would you choose each language? (Total should add up to 100) (Add more rows in you have more languages)

| Language | Percentage of usage |
|---|---|
| | |
| **Total** | **100** |

17. For all the languages you have learner or studied, mention the **age** at which you started using each of the languages in terms of listening, reading, writing and the total years you have spent using each language (Add more rows in you have more languages)

| Language | Listening | Speaking | Reading | Writing | Total years |
|---|---|---|---|---|---|
| | | | | | |

18. How much % of time in a day do you spend interacting with the following groups of people in each of the languages that you have mentioned (Add more rows in you have more languages)

| Language | Family members | Friends | Classmates | Others |
|---|---|---|---|---|
| | | | | |

19. If you tend to mix languages in your daily conversation, estimate the frequency of language mixing among the following groups of people on a scale of 1-7.

    1: None 2: Very weak 3: Weak 4: Moderate 5: Strong 6: Very strong 7: Extreme

| Language | Family members | Friends | Classmates | Others |
|---|---|---|---|---|
| | | | | |

20. In which language do you communicate best or feel most comfortable in terms of listening, speaking, reading, and writing in each of the following environments? You may be selecting the same language for all or some of the fields below.

| | Listening | Speaking | Reading | Writing |
|---|---|---|---|---|
| **At home** | | | | |
| **In class** | | | | |
| **With friends** | | | | |
| **Others** | | | | |

21. On a scale of 1- 7, how often do you use each of the languages that you know for the following activities? (Add more rows in you have more languages)

    1: Never; 2: Rarely; 3: Sometimes; 4: Regularly; 5: Often; 6: Usually; 7: Always

| Language | Thinking | Talking to yourself | Expressing emotion | Dreaming | Calculations | Remembering numbers | Praying |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | | | | | | | |

## Appendix D

### Language Usage Questionnaire

**Section 1 of 6: Instructions. Each page has a separate question. There are 5 questions in all. You have to respond to each question with a percentage score. Please make sure that your answers in each page add up to a total of 100. You may use '0' (zero) if the answer is 0. However, the total in each page has to add up to a 100.**

1. Participant name:

2. Roll number:

3. Email ID:

**Section 2 of 6: How much time (in percentage) do you spend in each of the following situations, in general? Please note, that your total for the next 4 situations in this section, together have to add up to 100.**

4. Home (or hostel room)

5. School (including online classes, lab work, etc.)

6. Social Interactions (include interactions among your peers face-to-face, on phone, etc.)

7. Non-social interactions (includes all interactions for instance, in the market, cab drivers, etc.)

8. Your total by adding your responses to questions 4, 5, 6, and 7 in this page.

**Section 3 of 6: In a day, how often do you switch between languages at home? You will be given 3 choices below. Answer them in terms of percentage. Your total in the 3 questions in this section should add up to 100. Please read the possible answers carefully. You may respond with a '0' (zero) if a question is not applicable to your situation.**

9. I speak only one language and rarely switch to the other language at home.

10. I speak 2 (or more) languages when I converse with different speakers at home. I often switch languages but rarely mix languages within one single conversation.

11. I routinely mix 2 (or more) languages within a conversation to most speakers at home.

12. Your total by adding your responses to questions 9, 10, and 11 in this page

**Section 4 of 6: In a day, how often do you switch between languages when at school? This may include during online classes, presentations, lab work, etc. You will be given 3 choices below. Answer them in terms of percentage. Your total in the 3 questions in this section should add up to 100. Please read the possible answers carefully. You may respond with a '0' (zero) if a question is not applicable to your situation.**

13. I speak only one language and rarely switch to the other language at school.

14. I speak 2 (or more) languages when I converse with different speakers at school. I often switch languages but rarely mix languages within one single conversation.

15. I routinely mix 2 (or more) languages within a conversation to most speakers at school.

16. Your total by adding your responses to questions 13, 14, and 15 in this page.

**Section 5 of 6: In a day, how often do you switch between languages in your social interactions? These interactions include all conversations you gave with your peers, whether it be face-to-face, on the phone, etc. You will be given 3 choices below. Answer them in terms of percentage. Your total in the 3 questions in this section should add up to 100. Please read the possible answers carefully. You may respond with a '0' (zero) if a question is not applicable to your situation.**

17. I speak only one language and rarely switch to the other language during my social interactions.

18. I speak 2 (or more) languages when I converse with different speakers during my social interactions. I often switch languages but rarely mix languages within one single conversation.

19. I routinely mix 2 (or more) languages within a conversation to most speakers during my social interactions.

20. Your total by adding your responses to questions 17, 18, and 19 in this page

**Section 6 of 6: In a day, how often do you switch between languages while having non-social interactions? These interactions may include those you have with shop vendors, cab drivers, security personnel, etc. You will be given 3 choices below. Answer them in terms of percentage. Your total in the 3 questions in this page should add up to 100. Please read the possible answers carefully. You may respond with a '0' (zero) if a question is not applicable to your situation.**

21. I speak only one language and rarely switch to the other language during non-social interactions.

22. I speak 2 (or more) languages when I converse with different speakers during non-social interactions. I often switch languages but rarely mix languages within one single conversation.

23. I routinely mix 2 (or more) languages within a conversation to most speakers during non-social interactions.

24. Your total by adding your responses to questions 21, 22, and 23 in this page

## Appendix E

### Univalent task: Pairwise analysis of EM means of fixed effects' interaction

#### *a) Overall analysis*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Pure (Letter) - Single Pure (Number) | 108.14 | 16.8 | 6236.8 | 6.45 | *< .0001* |
| Single Pure (Letter) - Dual Pure (Number) | 137.55 | 43.3 | 100.2 | 3.18 | *.08* |
| Single Pure (Letter) - Dense Pure (Number) | 88.77 | 42.0 | 98.6 | 2.11 | .61 |
| Single Alternate - Single Pure (Letter) | 2.96 | 14.3 | 6716.7 | 0.21 | 1.00 |
| Single Alternate - Dual Pure (Letter) | 125.85 | 42.3 | 91.7 | 2.98 | .13 |
| Single Alternate - Dense Pure (Letter) | 39.84 | 40.9 | 89.3 | 0.97 | .99 |
| Single Alternate - Single Pure (Number) | 111.10 | 14.2 | 6741.0 | 7.84 | *< .0001* |
| Single Alternate - Dual Pure (Number) | 140.51 | 42.2 | 91.2 | 3.33 | *.05* |
| Single Alternate - Dense Pure (Number) | 91.73 | 40.9 | 89.4 | 2.24 | .53 |
| Single Alternate - Single Mixed | 60.43 | 10.9 | 6784.9 | 5.55 | *< .0001* |
| Single Alternate – Dual Mixed | 118.03 | 41.1 | 82.2 | 2.87 | .17 |
| Single Alternate - Dense Mixed | 28.52 | 39.9 | 80.5 | 0.72 | .99 |
| Single Mixed - Single Pure (Letter) | -57.46 | 14.3 | 6715.1 | -4.02 | *.003* |
| Single Mixed - Dual Pure (Letter) | 65.43 | 42.4 | 92.4 | 1.55 | .92 |
| Single Mixed - Dense Pure (Letter) | -20.58 | 41.0 | 90.0 | -0.50 | 1.00 |
| Single Mixed - Single Pure (Number) | 50.68 | 14.2 | 6737.8 | 3.58 | *.02* |
| Single Mixed - Dual Pure (Number) | 80.09 | 42.3 | 91.9 | 1.89 | .76 |
| Single Mixed - Dense Pure (Number) | 31.31 | 41.0 | 90.1 | 0.76 | .99 |
| Dual Pure (Letter) - Single Pure (Letter) | -122.89 | 42.8 | 96.2 | -2.87 | .17 |
| Dual Pure (Letter) - Dense Pure (Letter) | -86.01 | 42.3 | 91.9 | -2.03 | .67 |
| Dual Pure (Letter) - Single Pure (Number) | -14.75 | 43.2 | 100.2 | -0.34 | 1.00 |
| Dual Pure (Letter) - Dual Pure (Number) | 14.66 | 17.4 | 6315.9 | 0.84 | .99 |
| Dual Pure (Letter) - Dense Pure (Number) | -34.12 | 42.8 | 96.1 | -0.80 | .99 |
| Dual Pure (Number) - Single Pure (Number) | -29.41 | 42.7 | 95.6 | -0.69 | .99 |
| Dual Pure (Number) - Dense Pure (Number) | -48.78 | 42.2 | 91.5 | -1.16 | .99 |
| Dual Alternate - Single Pure (Letter) | -78.16 | 42.1 | 90.4 | -1.86 | .78 |
| Dual Alternate - Dual Pure (Letter) | 44.73 | 14.7 | 6728.3 | 3.03 | .10 |
| Dual Alternate - Dense Pure (Letter) | -41.28 | 41.6 | 86.2 | -0.99 | .99 |
| Dual Alternate - Single Pure (Number) | 29.98 | 41.1 | 89.9 | 0.71 | .99 |
| Dual Alternate - Dual Pure (Number) | 59.39 | 14.7 | 6747.7 | 4.03 | *.003* |
| Dual Alternate - Dense Pure (Number) | 10.61 | 41.6 | 86.0 | 0.26 | 1.00 |
| Dual Alternate - Single Alternate | -81.13 | 41.0 | 81.3 | -1.98 | .71 |
| Dual Alternate - Dense Alternate | -95.03 | 40.5 | 77.3 | -2.35 | .45 |
| Dual Alternate - Single Mixed | -20.70 | 41.1 | 81.9 | -0.50 | 1.00 |
| Dual Alternate - Dual Mixed | 36.91 | 11.2 | 6782.8 | 3.29 | *.05* |
| Dual Alternate - Dense Mixed | -52.61 | 40.5 | 77.7 | -1.30 | .98 |
| Dual Mixed - Single Pure (Letter) | -115.07 | 42.2 | 91.4 | -2.72 | .23 |
| Dual Mixed - Dual Pure (Letter) | 7.82 | 14.7 | 6726.5 | 0.53 | 1.00 |
| Dual Mixed - Dense Pure (Letter) | -78.19 | 41.7 | 87.1 | -1.87 | .77 |
| Dual Mixed - Single Pure (Number) | -6.93 | 42.2 | 90.9 | 0.16 | 1.00 |
| Dual Mixed - Dual Pure (Number) | 22.48 | 14.8 | 6747.2 | 1.52 | .93 |
| Dual Mixed - Dense Pure (Number) | -26.30 | 41.7 | 86.9 | -0.63 | 1.00 |
| Dual Mixed - Single Mixed | -57.61 | 41.2 | 82.6 | -1.40 | .96 |
| Dual Mixed - Dense Mixed | -89.52 | 40.6 | 78.3 | -2.20 | .55 |
| Dense Pure (Letter) - Single Pure (Letter) | -36.88 | 41.4 | 93.9 | -0.89 | .99 |
| Dense Pure (Letter) - Single Pure (Number) | 71.26 | 41.9 | 98.2 | 1.70 | .86 |
| Dense Pure (Letter) - Dual Pure (Number) | 100.67 | 42.8 | 95.7 | 2.36 | .45 |
| Dense Pure (Letter) - Dense Pure (Number) | 51.89 | 16.8 | 6249.9 | 3.09 | *.09* |
| Dense Pure (Number) - Single Pure (Number) | 19.37 | 41.4 | 94.0 | 0.47 | 1.00 |

| | | | | | |
|---|---|---|---|---|---|
| Dense Alternate - Single Pure (Letter) | 16.87 | 40.9 | 89.4 | 0.41 | 1.00 |
| Dense Alternate - Dual Pure (Letter) | 139.76 | 41.8 | 87.5 | 3.35 | *.05* |
| Dense Alternate - Dense Pure (Letter) | 55.75 | 14.2 | 6721.2 | 3.78 | *.009* |
| Dense Alternate - Single Pure (Number) | 125.01 | 40.9 | 89.0 | 3.06 | .11 |
| Dense Alternate - Dual Pure (Number) | 154.42 | 41.7 | 86.9 | 3.70 | *.02* |
| Dense Alternate - Dense Pure (Number) | 105.64 | 14.3 | 6739.1 | 7.38 | *< .0001* |
| Dense Alternate - Single Alternate | 13.91 | 39.8 | 80.0 | 0.35 | 1.00 |
| Dense Alternate - Single Mixed | 74.33 | 39.9 | 80.5 | 1.87 | .78 |
| Dense Alternate - Dual Mixed | 131.94 | 40.6 | 78.1 | 3.25 | *.07* |
| Dense Alternate - Dense Mixed | 42.42 | 10.9 | 6784.0 | 3.89 | *.006* |
| Dense Mixed - Single Pure (Letter) | -25.55 | 41.0 | 90.0 | -0.62 | 1.00 |
| Dense Mixed - Dual Pure (Letter) | 97.34 | 41.8 | 88.0 | 2.33 | .47 |
| Dense Mixed - Dense Pure (Letter) | 11.33 | 14.2 | 6719.4 | 0.80 | .99 |
| Dense Mixed - Single Pure (Number) | 82.59 | 41.0 | 89.6 | 2.02 | .68 |
| Dense Mixed - Dual Pure (Number) | 112.00 | 41.8 | 87.5 | 2.68 | .25 |
| Dense Mixed - Dense Pure (Number) | 63.22 | 14.4 | 6738.6 | 4.41 | *.0007* |
| Dense Mixed - Single Mixed | 31.91 | 39.9 | 80.8 | 0.80 | .99 |

### *b) Local switch cost*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Repeat A - Single Repeat M | 56.85 | 34.2 | 102332.9 | 1.66 | .88 |
| Single Repeat A - Dual Repeat M | 98.90 | 53.9 | 215.7 | 1.84 | .80 |
| Single Repeat A - Dense Repeat M | 17.81 | 52.9 | 220.9 | 0.34 | 1.00 |
| Single Repeat A - Single Switch A | -107.32 | 16.4 | 4312.7 | -6.53 | *< .0001* |
| Single Repeat A - Dual Switch A | -13.10 | 44.4 | 99.0 | -0.30 | 1.00 |
| Single Repeat A - Dense Switch A | -107.97 | 43.1 | 97.8 | -2.50 | .35 |
| Single Repeat A - Single Switch M | -34.17 | 34.2 | 100301.1 | -0.99 | 1.00 |
| Single Repeat A - Dual Switch M | 48.99 | 53.8 | 213.3 | 0.91 | 1.00 |
| Single Repeat A - Dense Switch M | -66.66 | 52.7 | 218.2 | -1.27 | .98 |
| Single Repeat M - Single Switch A | -164.17 | 34.5 | 86316.0 | -4.76 | *.0001* |
| Single Repeat M - Dual Switch A | -69.96 | 53.8 | 214.5 | -1.30 | .98 |
| Single Repeat M - Dense Switch A | -164.82 | 52.8 | 219.3 | -3.12 | *.08* |
| Single Repeat M - Single Switch M | -91.02 | 15.9 | 4465.6 | -5.74 | *< .0001* |
| Single Repeat M - Dual Switch M | -7.87 | 44.5 | 100.3 | -0.18 | 1.00 |
| Single Repeat M - Dense Switch M | -123.51 | 43.2 | 98.4 | -2.86 | .17 |
| Single Switch A - Single Switch M | 73.15 | 34.1 | 106168.3 | 2.15 | .59 |
| Single Switch A - Dual Switch M | 156.30 | 53.5 | 209.4 | 2.92 | .14 |
| Single Switch A - Dense Switch M | 40.66 | 52.4 | 213.4 | 0.78 | 1.00 |
| Dual Repeat A - Single Repeat A | -87.84 | 44.3 | 98.6 | -1.98 | .70 |
| Dual Repeat A - Dense Repeat A | -103.03 | 43.6 | 92.7 | -2.36 | .44 |
| Dual Repeat A - Single Repeat M | -30.99 | 53.9 | 215.5 | -0.58 | 1.00 |
| Dual Repeat A - Dual Repeat M | 11.06 | 34.5 | 91324.9 | 0.32 | 1.00 |
| Dual Repeat A - Dense Repeat M | -70.04 | 53.3 | 205.9 | 1.31 | .98 |
| Dual Repeat A - Single Switch A | -195.16 | 44.5 | 99.7 | -4.39 | *.002* |
| Dual Repeat A - Dual Switch A | -100.95 | 16.8 | 4341.9 | -6.01 | *< .0001* |
| Dual Repeat A - Dense Switch A | -195.81 | 43.7 | 93.1 | -4.48 | *.001* |
| Dual Repeat A - Single Switch M | -122.01 | 53.8 | 213.5 | -2.27 | .50 |
| Dual Repeat A - Dual Switch M | -38.86 | 34.4 | 90491.1 | -1.13 | .99 |
| Dual Repeat A - Dense Switch M | -154.50 | 53.1 | 203.7 | -2.91 | .15 |
| Dual Repeat M - Single Repeat M | -42.05 | 44.6 | 101.3 | -0.94 | 1.00 |
| Dual Repeat M - Dense Repeat M | -81.09 | 43.9 | 94.6 | -1.85 | .79 |
| Dual Repeat M - Single Switch A | -206.22 | 53.9 | 215.8 | -3.82 | *.009* |
| Dual Repeat M - Dual Switch A | -112.01 | 34.7 | 80646.9 | -3.23 | *.06* |
| Dual Repeat M - Dense Switch A | -206.87 | 53.3 | 205.8 | -3.88 | *.008* |

| | | | | | |
|---|---|---|---|---|---|
| Dual Repeat M - Single Switch M | -133.07 | 44.6 | 100.5 | -2.99 | .13 |
| Dual Repeat M - Dual Switch M | -49.92 | 16.4 | 4476.2 | -3.04 | .10 |
| Dual Repeat M - Dense Switch M | -165.56 | 43.8 | 93.8 | -3.78 | *.01* |
| Dual Switch A - Single Switch A | -94.21 | 43.9 | 95.0 | -2.15 | .59 |
| Dual Switch A - Dense Switch A | -94.86 | 43.2 | 88.7 | -2.20 | .56 |
| Dual Switch A - Single Switch M | -21.06 | 53.5 | 208.7 | -0.39 | 1.00 |
| Dual Switch A - Dual Switch M | 62.09 | 34.3 | 98305.8 | 1.81 | .81 |
| Dual Switch A - Dense Switch M | -53.55 | 52.9 | 199.4 | -1.01 | 1.00 |
| Dual Switch M - Single Switch M | -83.15 | 44.0 | 96.1 | -1.89 | .76 |
| Dual Switch M - Dense Switch M | -115.64 | 43.3 | 89.7 | -2.67 | .26 |
| Dense Repeat A - Single Repeat A | 15.18 | 43.2 | 98.1 | 0.35 | 1.00 |
| Dense Repeat A - Single Repeat M | 72.04 | 52.9 | 221.5 | 1.36 | .97 |
| Dense Repeat A - Dual Repeat M | 114.09 | 53.3 | 206.7 | 2.14 | .60 |
| Dense Repeat A - Dense Repeat M | 32.99 | 34.2 | 100033.9 | 0.96 | 1.00 |
| Dense Repeat A - Single Switch A | -92.14 | 43.2 | 98.7 | -2.13 | .60 |
| Dense Repeat A - Dual Switch A | 2.08 | 43.7 | 93.3 | 0.05 | 1.00 |
| Dense Repeat A - Dense Switch A | -92.79 | 16.4 | 4323.5 | -5.65 | *< .0001* |
| Dense Repeat A - Single Switch M | -18.98 | 52.8 | 219.5 | -0.36 | 1.00 |
| Dense Repeat A - Dual Switch M | 64.17 | 53.2 | 204.8 | 1.21 | .99 |
| Dense Repeat A - Dense Switch M | -51.47 | 34.2 | 98765.8 | -1.50 | .94 |
| Dense Repeat M - Single Repeat M | 39.04 | 43.3 | 99.4 | 0.90 | 1.00 |
| Dense Repeat M - Single Switch A | -125.13 | 52.8 | 220.2 | -2.37 | .43 |
| Dense Repeat M - Single Switch A | -125.13 | 52.8 | 220.2 | -2.37 | .43 |
| Dense Repeat M - Dual Switch A | -30.91 | 53.3 | 205.3 | -0.58 | 1.00 |
| Dense Repeat M - Dense Switch A | -125.78 | 34.5 | 86260.3 | -3.65 | *.01* |
| Dense Repeat M - Single Switch M | -51.97 | 43.2 | 98.8 | -1.20 | .99 |
| Dense Repeat M - Dual Switch M | 31.18 | 43.8 | 93.9 | 0.71 | 1.00 |
| Dense Repeat M - Dense Switch M | -84.46 | 16.0 | 4453.7 | -5.29 | *< .0001* |
| Dense Switch A - Single Switch A | 0.65 | 42.6 | 93.0 | 0.02 | 1.00 |
| Dense Switch A - Single Switch M | 73.80 | 52.4 | 213.2 | 1.41 | .96 |
| Dense Switch A - Dual Switch M | 156.95 | 52.9 | 200.0 | 2.97 | .13 |
| Dense Switch A - Dense Switch M | 41.31 | 34.1 | 107684.1 | 1.21 | .99 |
| Dense Switch M - Single Switch M | 32.49 | 42.7 | 94.1 | 0.76 | 1.00 |

### *c) Global switch cost*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Pure (Letter) - Single Pure (Number) | 110.94 | 17.6 | 2850 | 6.30 | *< .0001* |
| Single Pure (Letter) - Dual Pure (Number) | 147.32 | 43.4 | 123 | 3.39 | *.04* |
| Single Pure (Letter) - Dense Pure (Number) | 107.44 | 42.2 | 121 | 2.55 | .32 |
| Single Alternate - Single Pure (Letter) | -9.55 | 15.7 | 4001 | -0.61 | 1.00 |
| Single Alternate - Dual Pure (Letter) | 112.18 | 42.7 | 116 | 2.63 | .28 |
| Single Alternate - Dense Pure (Letter) | 40.92 | 41.4 | 114 | 0.99 | 1.00 |
| Single Alternate - Single Pure (Number) | 101.39 | 15.2 | 4262 | 6.66 | *< .0001* |
| Single Alternate - Dual Pure (Number) | 137.77 | 42.5 | 114 | 3.24 | *.07* |
| Single Alternate - Dense Pure (Number) | 97.89 | 41.3 | 113 | 2.37 | .43 |
| Single Alternate - Single Mixed | 51.14 | 14.6 | 4384 | 3.49 | *.02* |
| Single Alternate - Dual Mixed | 88.44 | 42.3 | 113 | 2.09 | .63 |
| Single Alternate - Dense Mixed | 28.72 | 41.1 | 111 | 0.70 | 1.00 |
| Single Mixed - Single Pure (Letter) | -60.70 | 15.7 | 4124 | -3.87 | *.006* |
| Single Mixed - Dual Pure (Letter) | 61.04 | 42.8 | 117 | 1.43 | .96 |
| Single Mixed - Dense Pure (Letter) | -10.22 | 41.5 | 115 | -0.25 | 1.00 |
| Single Mixed - Single Pure (Number) | 50.25 | 15.4 | 4213 | 3.27 | *.05* |
| Single Mixed - Dual Pure (Number) | 86.63 | 42.7 | 116 | 2.03 | .67 |
| Single Mixed - Dense Pure (Number) | 46.75 | 41.4 | 114 | 1.13 | .99 |

| | | | | | |
|---|---|---|---|---|---|
| Dual Pure (Letter) - Single Pure (Letter) | -121.74 | 42.2 | 112 | -2.89 | .16 |
| Dual Pure (Letter) - Dense Pure (Letter) | -71.26 | 41.5 | 104 | -1.72 | .86 |
| Dual Pure (Letter) - Single Pure (Number) | -10.79 | 43.3 | 122 | -0.25 | 1.00 |
| Dual Pure (Letter) - Dual Pure (Number) | 25.59 | 18.1 | 2965 | 1.41 | .96 |
| Dual Pure (Letter) - Dense Pure (Number) | 14.29 | 42.6 | 114 | -0.33 | 1.00 |
| Dual Pure (Number) - Single Pure (Number) | -0.36.38 | 42.1 | 110 | -0.86 | 1.00 |
| Dual Pure (Number) - Dense Pure (Number) | -39.88 | 41.3 | 102 | -0.97 | 1.00 |
| Dual Alternate - Single Pure (Letter) | 91.97 | 42.5 | 114 | -2.16 | .58 |
| Dual Alternate - Dual Pure (Letter) | 29.76 | 16.2 | 4045 | 1.84 | .80 |
| Dual Alternate - Dense Pure (Letter) | -41.50 | 41.7 | 106 | -0.99 | 1.00 |
| Dual Alternate - Single Pure (Number) | 18.97 | 42.3 | 112 | 0.45 | 1.00 |
| Dual Alternate - Dual Pure (Number) | 55.35 | 15.8 | 4277 | 3.49 | *.02* |
| Dual Alternate - Dense Pure (Number) | 15.47 | 41.5 | 104 | 0.37 | 1.00 |
| Dual Alternate - Single Alternate | -82.42 | 42.0 | 110 | -1.96 | .72 |
| Dual Alternate - Dense Alternate | -85.12 | 41.3 | 102 | -2.06 | .65 |
| Dual Alternate - Single Mixed | -31.28 | 42.3 | 112 | -0.74 | 1.00 |
| Dual Alternate - Dual Mixed | 6.02 | 15.1 | 4383 | 0.40 | 1.00 |
| Dual Alternate - Dense Mixed | -53.70 | 41.4 | 103 | -1.30 | .98 |
| Dual Mixed - Single Pure (Letter) | -97.99 | 42.7 | 116 | -2.30 | .48 |
| Dual Mixed - Dual Pure (Letter) | 23.75 | 16.1 | 4152 | 1.48 | .95 |
| Dual Mixed - Dense Pure (Letter) | -47.51 | 41.9 | 107 | -1.14 | .99 |
| Dual Mixed - Single Pure (Number) | 12.96 | 42.5 | 114 | 0.31 | 1.00 |
| Dual Mixed - Dual Pure (Number) | 49.34 | 16.0 | 4235 | 3.08 | *.09* |
| Dual Mixed - Dense Pure (Number) | 9.45 | 41.7 | 106 | 0.23 | 1.00 |
| Dual Mixed - Single Mixed | -37.29 | 42.4 | 114 | -0.88 | 1.00 |
| Dual Mixed - Dense Mixed | -59.71 | 41.5 | 104 | -1.44 | .95 |
| Dense Pure Letter - Single Pure (Letter) | -50.48 | 40.9 | 109 | -1.23 | .98 |
| Dense Pure Letter - Single Pure (Number) | 60.47 | 42.1 | 120 | 1.44 | .95 |
| Dense Pure Letter - Dual Pure (Number) | 96.85 | 42.6 | 114 | 2.27 | .50 |
| Dense Pure Letter - Dense Pure (Number) | 56.97 | 17.7 | 2857 | 3.21 | *.06* |
| Dense Pure Number - Single Pure (Number) | 3.50 | 40.9 | 108 | 0.09 | 1.00 |
| Dense Alternate - Single Pure (Letter) | -6.85 | 41.5 | 114 | -0.17 | 1.00 |
| Dense Alternate - Dual Pure (Letter) | 114.89 | 42.0 | 108 | 2.74 | .22 |
| Dense Alternate - Dense Pure (Letter) | 43.63 | 15.8 | 4001 | 2.77 | .20 |
| Dense Alternate - Single Pure (Number) | 104.10 | 41.2 | 112 | 2.53 | .34 |
| Dense Alternate - Dual Pure (Number) | 140.48 | 41.7 | 106 | 3.37 | *.05* |
| Dense Alternate - Dense Pure (Number) | 100.59 | 15.5 | 4266 | 6.51 | *< .0001* |
| Dense Alternate - Single Alternate | 2.70 | 41.0 | 110 | 0.07 | 1.00 |
| Dense Alternate - Single Mixed | 53.85 | 41.2 | 112 | 1.31 | .98 |
| Dense Alternate - Dual Mixed | 91.14 | 41.5 | 105 | 2.20 | .56 |
| Dense Alternate - Dense Mixed | 31.42 | 14.8 | 4383 | 2.12 | .61 |
| Dense Mixed - Single Pure (Letter) | -38.27 | 41.4 | 114 | -0.92 | 1.00 |
| Dense Mixed - Dual Pure (Letter) | 83.46 | 41.9 | 108 | 1.99 | .70 |
| Dense Mixed - Dense Pure (Letter) | 12.20 | 15.7 | 4143 | 0.78 | 1.00 |
| Dense Mixed - Single Pure (Number) | 72.67 | 41.3 | 113 | 1.76 | .84 |
| Dense Mixed - Dual Pure (Number) | 109.05 | 41.8 | 107 | 2.61 | .29 |
| Dense Mixed - Dense Pure (Number) | 69.17 | 15.7 | 4203 | 4.40 | *.0007* |
| Dense Mixed - Single Mixed | 22.42 | 41.2 | 112 | 0.55 | 1.00 |

# Appendix F

## Bivalent task: Pairwise analysis of EM means of fixed effects' interaction

### *a) Overall analysis*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Pure Colour - Single Pure Shape | -57.17 | 20.9 | 4342.8 | -2.73 | .21 |
| Single Pure Colour - Dual Pure Shape | 16.32 | 49.2 | 119.9 | 0.33 | 1.00 |
| Single Pure Colour - Dense Pure Shape | -166.26 | 47.0 | 110.5 | -3.54 | *.03* |
| Single Alternate - Single Pure Colour | 72.90 | 18.8 | 337.6 | 3.88 | *.007* |
| Single Alternate - Dual Pure Colour | 38.97 | 48.4 | 106.5 | 0.81 | 1.00 |
| Single Alternate - Dense Pure Colour | -83.23 | 46.1 | 97.4 | -1.81 | .81 |
| Single Alternate - Single Pure Shape | 15.72 | 18.8 | 295.1 | 0.84 | 1.00 |
| Single Alternate - Dual Pure Shape | 89.21 | 48.3 | 105.1 | 1.85 | .79 |
| Single Alternate - Dense Pure Shape | -93.36 | 45.9 | 95.6 | -2.03 | .67 |
| Single Alternate - Single Mixed | -6.80 | 13.4 | 6837.3 | -0.51 | 1.00 |
| Single Alternate - Dual Mixed | -13.60 | 46.3 | 95.2 | -0.29 | 1.00 |
| Single Alternate - Dense Mixed | -144.07 | 44.0 | 85.9 | -3.28 | *.06* |
| Single Mixed - Single Pure Colour | 79.70 | 19.1 | 237.1 | 4.18 | *.002* |
| Single Mixed - Dual Pure Colour | 45.77 | 48.5 | 106.4 | 0.94 | 1.00 |
| Single Mixed - Dense Pure Colour | -76.42 | 46.2 | 97.4 | -1.65 | .88 |
| Single Mixed - Single Pure Shape | 22.53 | 19.1 | 210.1 | 1.18 | .99 |
| Single Mixed - Dual Pure Shape | 96.02 | 48.5 | 105.0 | 1.98 | .70 |
| Single Mixed - Dense Pure Shape | -86.56 | 46.1 | 95.7 | -1.88 | .77 |
| Dual Pure Colour - Single Pure Colour | 33.93 | 48.6 | 115.4 | 0.70 | 1.00 |
| Dual Pure Colour - Dense Pure Colour | -122.19 | 48.5 | 114.5 | -2.52 | .34 |
| Dual Pure Colour - Single Pure Shape | -23.24 | 49.2 | 119.4 | -0.47 | 1.00 |
| Dual Pure Colour - Dual Pure Shape | 50.25 | 21.7 | 4558.9 | 2.32 | .46 |
| Dual Pure Colour - Dense Pure Shape | -132.32 | 49.1 | 118.4 | -2.70 | .24 |
| Dual Pure Shape - Single Pure Shape | -73.49 | 48.2 | 112.2 | -1.52 | .93 |
| Dual Pure Shape - Dense Pure Shape | -182.57 | 48.1 | 111.0 | -3.79 | *.01* |
| Dual Alternate - Single Pure Colour | 96.52 | 48.4 | 107.3 | 1.99 | .70 |
| Dual Alternate - Dual Pure Colour | 62.59 | 19.5 | 419.8 | 3.21 | *.06* |
| Dual Alternate - Dense Pure Colour | -59.60 | 48.2 | 106.2 | -1.24 | .98 |
| Dual Alternate - Single Pure Shape | 39.35 | 48.2 | 105.4 | 0.82 | 1.00 |
| Dual Alternate - Dual Pure Shape | 112.84 | 19.3 | 344.5 | 5.85 | < *.0001* |
| Dual Alternate - Dense Pure Shape | -69.73 | 48.0 | 104.4 | -1.45 | .95 |
| Dual Alternate - Dense Alternate | -129.65 | 46.4 | 96.4 | -2.79 | .20 |
| Dual Alternate - Single Alternate | 23.63 | 46.5 | 96.9 | 0.51 | 1.00 |
| Dual Alternate - Single Mixed | 16.82 | 46.5 | 97.1 | 0.36 | 1.00 |
| Dual Alternate - Dual Mixed | 10.03 | 13.9 | 6828.7 | 0.72 | 1.00 |
| Dual Alternate - Dense Mixed | -120.44 | 46.3 | 94.7 | -2.60 | .29 |
| Dual Mixed - Single Pure Colour | 86.50 | 48.3 | 105.2 | 1.79 | .82 |
| Dual Mixed - Dual Pure Colour | 52.56 | 19.7 | 279.5 | 2.66 | .25 |
| Dual Mixed - Dense Pure Colour | -69.63 | 48.1 | 104.2 | -1.45 | .95 |
| Dual Mixed - Single Pure Shape | 29.32 | 48.1 | 103.4 | 0.61 | 1.00 |
| Dual Mixed - Dual Pure Shape | 102.81 | 19.6 | 232.2 | 5.25 | < *.0001* |
| Dual Mixed - Dense Pure Shape | -79.76 | 48.0 | 102.5 | -1.66 | .88 |
| Dual Mixed - Single Mixed | 6.79 | 46.3 | 95.4 | 20.15 | 1.00 |
| Dual Mixed - Dense Mixed | -130.47 | 46.0 | 93.0 | -2.84 | .18 |
| Dense Pure Colour - Single Pure Colour | 156.12 | 46.4 | 106.4 | 3.36 | *.05* |
| Dense Pure Colour - Single Pure Shape | 98.95 | 47.0 | 110.1 | 2.11 | .62 |
| Dense Pure Colour - Dual Pure Shape | 172.44 | 49.1 | 118.5 | 3.51 | *.03* |
| Dense Pure Colour - Dense Pure Shape | -10.13 | 21.2 | 4424.3 | -0/48 | 1.00 |
| Dense Pure Shape - Single Pure Shape | 109.08 | 46.0 | 102.6 | 2.37 | .43 |

| | | | | | |
|---|---|---|---|---|---|
| Dense Alternate - Single Pure Colour | 226.17 | 46.3 | 98.1 | 4.89 | *.0002* |
| Dense Alternate - Dual Pure Colour | 192.24 | 48.4 | 106.1 | 391.1 | *.007* |
| Dense Alternate - Dense Pure Colour | 70.05 | 19.0 | 365.8 | 3.69 | *.01* |
| Dense Alternate - Single Pure Shape | 169.0 | 46.1 | 95.9 | 3.67 | *.02* |
| Dense Alternate - Dual Pure Shape | 242.49 | 48.3 | 104.3 | 5.03 | *.0001* |
| Dense Alternate - Dense Pure Shape | 59.92 | 18.9 | 313.3 | 3.17 | *.07* |
| Dense Alternate - Single Alternate | 153.28 | 44.2 | 87.7 | 3.47 | *.04* |
| Dense Alternate - Single Mixed | 146.47 | 44.2 | 87.9 | 3.31 | *.06* |
| Dense Alternate - Dual Mixed | 139.68 | 46.2 | 94.8 | 3.02 | .12 |
| Dense Alternate - Dense Mixed | 9.21 | 13.6 | 6838.4 | 0.68 | 1.00 |
| Dense Mixed - Single Pure Colour | 216.97 | 46.2 | 95.9 | 4.70 | *.0005* |
| Dense Mixed - Dual Pure Colour | 183.03 | 48.3 | 104.0 | 3.79 | *.01* |
| Dense Mixed - Dense Pure Colour | 60.84 | 19.2 | 255.4 | 3.16 | *.07* |
| Dense Mixed - Single Pure Shape | 159.79 | 46.0 | 93.9 | 3.47 | *.04* |
| Dense Mixed - Dual Pure Shape | 233.28 | 48.2 | 102.3 | 4.84 | *.0003* |
| Dense Mixed - Dense Pure Shape | 50.71 | 19.2 | 220.6 | 2.64 | .26 |
| Dense Mixed - Single Mixed | 137.27 | 44.0 | 86.1 | 3.12 | *.09* |

### *b) Local switch cost*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Repeat A - Dual Repeat M | -24.68 | 57.2 | 111.8 | -0.43 | 1.00 |
| Single Repeat A - Dense Repeat M | -142.62 | 54.1 | 98.8 | -2.64 | .27 |
| Single Repeat A - Single Repeat M | -19.29 | 21.2 | 5156.0 | -0.91 | 1.00 |
| Single Repeat A - Dual Switch A | -40.60 | 57.5 | 113.7 | -0.71 | 1.00 |
| Single Repeat A - Dense Switch A | -177.63 | 54.1 | 98.8 | -3.29 | *.06* |
| Single Repeat A - Single Switch A | -10.10 | 20.1 | 4617.5 | -0.50 | 1.00 |
| Single Repeat A - Dual Switch M | -33.47 | 57.3 | 112.7 | -0.58 | 1.00 |
| Single Repeat A - Dense Switch M | -187.08 | 54.1 | 98.9 | -3.46 | *.04* |
| Single Repeat A - Single Switch M | -12.06 | 20.2 | 5211.9 | -0.60 | 1.00 |
| Single Switch A - Dual Switch M | -23.38 | 57.4 | 113.6 | -0.41 | 1.00 |
| Single Switch A - Dense Switch M | -176.98 | 54.2 | 99.9 | -3.26 | *.06* |
| Single Switch A - Single Switch M | -1.96 | 20.3 | 5209.4 | -0.10 | 1.00 |
| Single Repeat M - Dual Switch A | -21.31 | 57.8 | 116.2 | -0.37 | 1.00 |
| Single Repeat M - Dense Switch A | -158.34 | 54.4 | 101.4 | -2.91 | .15 |
| Single Repeat M - Single Switch A | 9.19 | 21.2 | 5153.1 | 0.43 | 1.00 |
| Single Repeat M - Dual Switch M | -14.18 | 57.3 | 112.1 | -0.25 | 1.00 |
| Single Repeat M - Dense Switch M | -167.79 | 54.0 | 98.5 | -3.11 | .10 |
| Single Repeat M - Single Switch M | 7.23 | 20.3 | 4615.6 | 0.36 | 1.00 |
| Dual Repeat A - Dense Repeat A | -131.84 | 57.2 | 111.3 | -2.31 | .48 |
| Dual Repeat A - Single Repeat A | 52.16 | 57.2 | 111.8 | 0.91 | 1.00 |
| Dual Repeat A - Dual Repeat M | 27.48 | 22.0 | 5113.3 | 1.25 | .98 |
| Dual Repeat A - Dense Repeat M | -90.46 | 57.0 | 110.2 | -1.59 | *.01* |
| Dual Repeat A - Single Repeat M | 32.87 | 57.5 | 114.4 | 0.57 | 1.00 |
| Dual Repeat A - Dual Switch A | 11.56 | 21.0 | 4617.3 | 0.55 | 1.00 |
| Dual Repeat A - Dense Switch A | -125.46 | 57.0 | 110.3 | -2.20 | .55 |
| Dual Repeat A - Single Switch A | 42.07 | 57.3 | 112.8 | 0.73 | 1.00 |
| Dual Repeat A - Dual Switch M | 18.69 | 21.0 | 5166.1 | 0.89 | 1.00 |
| Dual Repeat A - Dense Switch M | -134.91 | 57.1 | 110.6 | -2.36 | .44 |
| Dual Repeat A - Single Switch M | 40.10 | 57.5 | 113.9 | 0.70 | 1.00 |
| Dual Repeat M - Dense Repeat M | -117.93 | 56.6 | 106.7 | -2.09 | .63 |
| Dual Repeat M - Single Repeat M | 5.40 | 57.1 | 110.8 | 0.10 | 1.00 |
| Dual Repeat M - Dual Switch A | -15.92 | 22.1 | 5107.6 | -0.72 | 1.00 |
| Dual Repeat M - Dense Switch A | -152.94 | 57.0 | 110.3 | -2.68 | .25 |
| Dual Repeat M - Single Switch A | 14.59 | 57.3 | 112.7 | 0.25 | 1.00 |

| | | | | | |
|---|---|---|---|---|---|
| Dual Repeat M - Dual Switch M | -8.79 | 21.1 | 4617.0 | -0.42 | 1.00 |
| Dual Repeat M - Dense Switch M | -162.39 | 56.7 | 107.5 | -2.87 | .17 |
| Dual Repeat M - Single Switch M | 12.63 | 57.1 | 110.8 | 0.22 | 1.00 |
| Dual Switch A - Dense Switch A | -137.03 | 57.3 | 112.1 | -2.39 | .42 |
| Dual Switch A - Single Switch A | 30.50 | 57.6 | 114.6 | 0.53 | 1.00 |
| Dual Switch A - Dual Switch M | 7.13 | 21.1 | 5161.2 | 0.34 | 1.00 |
| Dual Switch A - Dense Switch M | -146.48 | 57.3 | 112.4 | -2.56 | .32 |
| Dual Switch A - Single Switch M | 28.54 | 57.7 | 115.8 | 0.49 | 1.00 |
| Dual Switch M - Dense Switch M | -153.60 | 56.7 | 108.0 | -2.71 | .24 |
| Dual Switch M - Single Switch M | 21.41 | 57.2 | 111.3 | 0.38 | 1.00 |
| Dense Repeat A - Single Repeat A | 184.00 | 54.2 | 99.8 | 3.39 | *.04* |
| Dense Repeat A - Dual Repeat M | 159.31 | 57.2 | 111.3 | 2.79 | .20 |
| Dense Repeat A - Dense Repeat M | 41.38 | 21.5 | 5141.8 | 1.93 | .74 |
| Dense Repeat A - Single Repeat M | 164.71 | 54.6 | 102.4 | 3.02 | .12 |
| Dense Repeat A - Dual Switch A | 143.40 | 57.4 | 113.1 | 2.50 | .35 |
| Dense Repeat A - Dense Switch A | 6.37 | 20.3 | 4617.2 | 0.31 | 1.00 |
| Dense Repeat A - Single Switch A | 173.90 | 54.3 | 100.7 | 3.20 | *.07* |
| Dense Repeat A - Dual Switch M | 150.52 | 57.3 | 112.1 | 2.63 | .28 |
| Dense Repeat A - Dense Switch M | -3.08 | 20.4 | 5198.4 | -0.15 | 1.00 |
| Dense Repeat A - Single Switch M | 171.94 | 54.5 | 101.8 | 3.16 | .08 |
| Dense Repeat M - Single Repeat M | 123.33 | 53.9 | 97.9 | 2.29 | .49 |
| Dense Repeat M - Dual Switch A | 102.02 | 57.3 | 112.0 | 1.78 | .82 |
| Dense Repeat M - Dense Switch A | -35.01 | 21.4 | 5145.4 | -1.64 | .90 |
| Dense Repeat M - Single Switch A | 132.52 | 54.2 | 99.7 | 2.45 | .39 |
| Dense Repeat M - Dual Switch M | 109.15 | 56.7 | 108.0 | 1.92 | .74 |
| Dense Repeat M - Dense Switch M | -44.46 | 20.4 | 4615.8 | -2.18 | .57 |
| Dense Repeat M - Single Switch M | 130.56 | 53.9 | 97.7 | 2.42 | .40 |
| Dense Switch A - Single Switch A | 167.53 | 54.2 | 99.7 | 3.09 | .10 |
| Dense Switch A - Dual Switch M | 144.15 | 57.1 | 111.1 | 2.52 | .34 |
| Dense Switch A - Dense Switch M | -9.45 | 20.4 | 5200.5 | -0.46 | 1.00 |
| Dense Switch A - Single Switch M | 165.57 | 54.3 | 100.8 | 3.05 | .11 |
| Dense Switch M - Single Switch M | 175.02 | 53.9 | 97.5 | 3.25 | .07 |

### *c) Global switch cost*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Pure Colour - Dual Pure Shape | 40.43 | 49.0 | 130 | 0.83 | 1.00 |
| Single Pure Colour - Dense Pure Shape | -135.65 | 46.9 | 120 | -2.90 | .16 |
| Single Pure Colour - Single Pure Shape | -41.61 | 21.4 | 2222 | -1.95 | .73 |
| Single Alternate - Dual Mixed | -3.28 | 47.3 | 116 | -0.07 | 1.00 |
| Single Alternate - Dense Mixed | -116.59 | 45.1 | 106 | -2.59 | .30 |
| Single Alternate - Single Mixed | -18.57 | 18.3 | 4404 | -1.01 | 1.00 |
| Single Alternate - Dual Pure Colour | 36.57 | 47.8 | 121 | 0.76 | 1.00 |
| Single Alternate - Dense Pure Colour | -72.27 | 45.9 | 113 | -1.57 | .91 |
| Single Alternate - Single Pure Colour | 59.05 | 18.8 | 4048 | 3.14 | *.07* |
| Single Alternate - Dual Pure Shape | 99.49 | 47.7 | 119 | 2.08 | .63 |
| Single Alternate - Dense Pure Shape | -76.60 | 45.6 | 110 | -1.68 | .87 |
| Single Alternate - Single Pure Shape | 17.44 | 18.8 | 4045 | .93 | 1.00 |
| Single Mixed - Dual Pure Colour | 55.14 | 47.9 | 122 | 1.15 | .99 |
| Single Mixed - Dense Pure Colour | -53.71 | 46.0 | 114 | -1.17 | 1.00 |
| Single Mixed - Single Pure Colour | 77.62 | 19.3 | 4106 | 4.03 | *.003* |
| Single Mixed - Dual Pure Shape | 118.05 | 47.9 | 121 | 2.47 | .37 |
| Single Mixed - Dense Pure Shape | -58.03 | 45.7 | 111 | -1.27 | .98 |
| Single Mixed - Single Pure Shape | 36.01 | 19.3 | 4054 | 1.87 | .78 |
| Dual Pure Colour - Dense Pure Colour | -108.84 | 47.9 | 121 | -2.28 | .50 |

| | | | | | |
|---|---|---|---|---|---|
| Dual Pure Colour - Single Pure Colour | 22.48 | 47.7 | 120 | .47 | 1.00 |
| Dual Pure Colour - Dual Pure Shape | 62.92 | 22.0 | 2344 | 2.86 | .16 |
| Dual Pure Colour - Dense Pure Shape | -113.17 | 48.9 | 129 | -2.31 | .47 |
| Dual Pure Colour - Single Pure Shape | -19.13 | 48.9 | 129 | -0.39 | 1.00 |
| Dual Pure Shape - Dense Pure Shape | -176.09 | 47.4 | 117 | -3.71 | *.02* |
| Dual Pure Shape - Single Pure Shape | -82.05 | 47.3 | 116 | -1.73 | .85 |
| Dual Alternate - Dense Alternate | -130.78 | 47.8 | 121 | -2.75 | .22 |
| Dual Alternate - Single Alternate | 16.05 | 47.4 | 117 | 0.34 | 1.00 |
| Dual Alternate - Dual Mixed | 12.77 | 19.1 | 4404 | .67 | 1.00 |
| Dual Alternate - Dense Mixed | -100.54 | 47.4 | 117 | -2.12 | .61 |
| Dual Alternate - Single Mixed | -2.52 | 47.6 | 110 | -0.05 | 1.00 |
| Dual Alternate - Dual Pure Colour | 52.62 | 19.7 | 4103 | 2.67 | .24 |
| Dual Alternate - Dense Pure Colour | -56.22 | 48.2 | 124 | -1.17 | .99 |
| Dual Alternate - Single Pure Colour | 75.11 | 48.0 | 122 | 1.57 | .92 |
| Dual Alternate - Dual Pure Shape | 115.54 | 19.4 | 4085 | 5.95 | < *.0001* |
| Dual Alternate - Dense Pure Shape | -60.55 | 47.8 | 121 | -1.27 | .98 |
| Dual Alternate - Single Pure Shape | 33.49 | 47.8 | 120 | .70 | 1.00 |
| Dual Mixed - Dense Mixed | -113.31 | 47.2 | 115 | -2.40 | .41 |
| Dual Mixed - Single Mixed | -15.29 | 47.4 | 116 | -0.32 | 1.00 |
| Dual Mixed - Dual Pure Colour | 39.85 | 20.0 | 4147 | 1.99 | .70 |
| Dual Mixed - Dense Pure Colour | -68.99 | 48.0 | 122 | -1.44 | .95 |
| Dual Mixed - Single Pure Colour | 62.33 | 47.8 | 120 | 1.30 | .98 |
| Dual Mixed - Dual Pure Shape | 102.77 | 19.9 | 4089 | 5.18 | < *.0001* |
| Dual Mixed - Dense Pure Shape | -73.32 | 47.7 | 119 | -1.54 | .93 |
| Dual Mixed - Single Pure Shape | 20.72 | 47.6 | 118 | 0.44 | 1.00 |
| Dense Pure Colour - Single Pure Colour | 131.33 | 45.7 | 112 | 2.87 | .17 |
| Dense Pure Colour - Dual Pure Shape | 171.76 | 49.2 | 132 | 3.49 | *.03* |
| Dense Pure Colour - Dense Pure Shape | -4.33 | 21.6 | 2269 | -0.20 | 1.00 |
| Dense Pure Colour - Single Pure Shape | 89.71 | 47.0 | 122 | 1.91 | .75 |
| Dense Pure Shape - Single Pure Shape | 94.04 | 45.2 | 107 | 2.08 | .64 |
| Dense Alternate - Single Alternate | 146.83 | 45.5 | 110 | 3.23 | *.07* |
| Dense Alternate - Dual Mixed | 143.55 | 47.6 | 119 | 3.01 | .12 |
| Dense Alternate - Dense Mixed | 30.24 | 18.6 | 4406 | 1.62 | .90 |
| Dense Alternate - Single Mixed | 128.26 | 45.7 | 111 | 2.81 | .19 |
| Dense Alternate - Dual Pure Colour | 183.40 | 48.2 | 124 | 3.80 | *.01* |
| Dense Alternate - Dense Pure Colour | 74.56 | 19.2 | 4053 | 3.89 | *.006* |
| Dense Alternate - Single Pure Colour | 205.88 | 46.1 | 115 | 4.47 | *.001* |
| Dense Alternate - Dual Pure Shape | 246.32 | 48.1 | 123 | 5.21 | *.0001* |
| Dense Alternate - Dense Pure Shape | 70.23 | 19.0 | 4083 | 3.70 | *.01* |
| Dense Alternate - Single Pure Shape | 164.27 | 45.9 | 113 | 3.58 | *.02* |
| Dense Mixed - Single Mixed | 98.02 | 45.2 | 107 | 2.17 | .58 |
| Dense Mixed - Dual Pure Colour | 153.16 | 47.8 | 120 | 3.21 | *.07* |
| Dense Mixed - Dense Pure Colour | 44.32 | 19.5 | 4136 | 2.27 | .50 |
| Dense Mixed - Single Pure Colour | 175.64 | 45.7 | 111 | 3.85 | *.01* |
| Dense Mixed - Dual Pure Shape | 216.08 | 47.7 | 119 | 4.53 | *.0008* |
| Dense Mixed - Dense Pure Shape | 39.99 | 19.4 | 4049 | 2.06 | .65 |
| Dense Mixed - Single Pure Shape | 134.03 | 45.5 | 109 | 2.95 | .14 |

# Appendix G

## N-Back task: Pairwise analysis of EM means of fixed effects' interaction

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single 1 Back - Single 2 Back | -122.56 | 14.6 | 6837.4 | -8.39 | < .0001 |
| Single 1 Back - Dual 2 Back | -12.49 | 47.0 | 80.4 | -0.26 | 1.00 |
| Single 1 Back - Dense 2 Back | -98.61 | 46.2 | 82.7 | -2.14 | .46 |
| Single 1 Back - Single 3 Back | -162.32 | 14.7 | 6868.4 | -11.01 | < .0001 |
| Single 1 Back - Dual 3 Back | -117.27 | 46.6 | 77.8 | -2.51 | .24 |
| Single 1 Back - Dense 3 Back | -146.28 | 45.9 | 81.0 | -3.19 | .05 |
| Single 2 Back - Single 3 Back | 39.76 | 14.7 | 6941.5 | -2.70 | .15 |
| Single 2 Back - Dual 3 Back | 5.29 | 46.5 | 76.9 | 0.11 | 1.00 |
| Single 2 Back - Dense 3 Back | -23.72 | 45.8 | 80.0 | -0.52 | 1.00 |
| Dual 1 Back - Single 1 Back | -25.80 | 47.0 | 80.4 | -0.55 | 1.00 |
| Dual 1 Back - Single 1 Back | -25.80 | 47.0 | 80.4 | -0.55 | 1.00 |
| Dual 1 Back - Dual 2 Back | -38.29 | 15.2 | 6850.1 | -2.52 | .22 |
| Dual 1 Back - Dense 1 Back | 7.41 | 47.2 | 81.3 | .16 | 1.00 |
| Dual 1 Back - Single 2 Back | -148.36 | 46.9 | 79.6 | -3.16 | .05 |
| Dual 1 Back - Dense 2 Back | 124.40 | 47.2 | 81.5 | -2.64 | .19 |
| Dual 1 Back - Single 3 Back | -188.12 | 46.7 | 78.0 | -4.03 | .004 |
| Dual 1 Back - Dual 3 Back | -143.07 | 15.4 | 6847.6 | -9.27 | < .0001 |
| Dual 1 Back - Dense 3 Back | -172.08 | 47.0 | 79.9 | -3.66 | 0.01 |
| Dual 2 Back - Single 2 Back | -110.07 | 46.9 | 79.3 | -2.35 | .33 |
| Dual 2 Back - Dense 2 Back | -86.11 | 47.2 | 81.3 | -1.83 | .66 |
| Dual 2 Back - Single 3 Back | -149.83 | 46.7 | 77.9 | -3.21 | .05 |
| Dual 2 Back - Dual 3 Back | -104.78 | 15.4 | 6956.4 | -6.80 | < .0001 |
| Dual 2 Back - Dense 3 Back | -133.79 | 46.9 | 79.8 | -2.85 | .12 |
| Dual 3 Back - Single 3 Back | -45.05 | 46.3 | 75.3 | -0.97 | .99 |
| Dual 3 Back - Dense 3 Back | -29.01 | 46.6 | 77.2 | -0.62 | 1.00 |
| Dense 1 Back - Single 1 Back | -33.21 | 46.1 | 82.5 | -0.72 | 1.00 |
| Dense 1 Back - Single 2 Back | -155.77 | 46.0 | 81.6 | -3.39 | 0.03 |
| Dense 1 Back - Dual 2 Back | -45.70 | 47.2 | 81.3 | -0.97 | .99 |
| Dense 1 Back - Dense 2 Back | -131.82 | 14.5 | 6819.2 | -9.08 | < .0001 |
| Dense 1 Back - Single 3 Back | 195.53 | 45.8 | 80.0 | -4.27 | .002 |
| Dense 1 Back - Dual 3 Back | -150.48 | 46.8 | 78.7 | -3.22 | .05 |
| Dense 1 Back - Dense 3 Back | -179.49 | 14.6 | 6781.1 | -12.32 | < .0001 |
| Dense 2 Back - Single 2 Back | -23.95 | 46.0 | 81.6 | -0.52 | 1.00 |
| Dense 2 Back - Single 3 Back | -63.71 | 45.8 | 80.0 | -1.39 | .90 |
| Dense 2 Back - Dual 3 Back | -18.66 | 46.8 | 78.8 | -0.40 | 1.00 |
| Dense 2 Back - Dense 3 Back | 47.68 | 14.6 | 6951.4 | -3.26 | .03 |
| Dense 3 Back - Single 3 Back | -16.04 | 45.5 | 78.4 | -0.35 | 1.00 |

# Appendix H

## Simon task: Pairwise analysis of EM means of fixed effects' interaction

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Congruent - Single Neutral | 11.67 | 9.16 | 3.77 | 1.28 | .90 |
| Single Congruent - Dual Neutral | -4.07 | 30.31 | 106.79 | -0.13 | 1.00 |
| Single Congruent - Dense Neutral | -20.68 | 29.35 | 102.12 | -0.71 | 1.00 |
| Single Congruent - Single Incongruent | 2.44 | 7.50 | 8.47 | 0.33 | 1.00 |
| Single Congruent - Dual Incongruent | -11.40 | 29.68 | 121.25 | -0.38 | 1.00 |
| Single Congruent - Dense Incongruent | 0.67 | 28.83 | 119.97 | 0.023 | 1.00 |
| Single Incongruent - Single Neutral | 9.23 | 9.15 | 3.76 | 1.01 | .96 |
| Single Incongruent - Dual Neutral | -6.51 | 30.09 | 103.92 | -0.22 | 1.00 |
| Single Incongruent - Dense Neutral | -23.12 | 29.13 | 99.19 | -0.79 | 1.00 |
| Dual Neutral - Single Neutral | 15.74 | 29.80 | 131.45 | 0.53 | 1.00 |
| Dual Neutral - Dense Neutral | -16.61 | 28.41 | 109.45 | -0.59 | 1.00 |
| Dual Congruent - Single Neutral | 24.98 | 30.27 | 106.24 | 0.83 | 1.00 |
| Dual Congruent - Dual Neutral | 9.24 | 9.50 | 4.37 | 0.97 | .97 |
| Dual Congruent - Dense Neutral | -7.37 | 28.80 | 89.20 | -0.26 | 1.00 |
| Dual Congruent - Single Congruent | 13.31 | 29.83 | 131.99 | 0.45 | 1.00 |
| Dual Congruent - Dense Congruent | 22.48 | 28.36 | 108.65 | 0.79 | 1.00 |
| Dual Congruent - Single Incongruent | 15.75 | 29.62 | 120.48 | 0.53 | 1.00 |
| Dual Congruent - Dual Incongruent | 1.92 | 7.90 | 10.44 | 0.24 | 1.00 |
| Dual Congruent - Dense Incongruent | 13.98 | 28.37 | 102.45 | .49 | 1.00 |
| Dual Incongruent - Single Neutral | 23.07 | 30.12 | 104.02 | 0.77 | 1.00 |
| Dual Incongruent - Dual Neutral | 7.32 | 9.47 | 4.31 | 0.77 | 1.00 |
| Dual Incongruent - Dense Neutral | -9.28 | 28.73 | 87.16 | -0.32 | 1.00 |
| Dual Incongruent - Single Incongruent | 13.84 | 29.46 | 125.53 | 0.47 | 1.00 |
| Dual Incongruent - Dense Incongruent | 12.06 | 28.21 | 106.33 | 0.43 | 1.00 |
| Dense Neutral - Single Neutral | 32.35 | 28.83 | 128.27 | 1.12 | .97 |
| Dense Congruent - Single Neutral | 2.50 | 29.27 | 101.00 | 0.09 | 1.00 |
| Dense Congruent - Dual Neutral | 13.24 | 28.86 | 88.69 | -0.46 | 1.00 |
| Dense Congruent - Dense Neutral | -29.85 | 9.25 | 3.90 | -3.23 | .23 |
| Dense Congruent - Single Congruent | -9.17 | 28.82 | 128.10 | -0.32 | 1.00 |
| Dense Congruent - Single Incongruent | -6.73 | 28.60 | 116.17 | -0.24 | 1.00 |
| Dense Congruent - Dual Incongruent | -20.57 | 28.19 | 99.79 | -0.73 | 1.00 |
| Dense Congruent - Dense Incongruent | -8.51 | 7.57 | 8.79 | -1.12 | .95 |
| Dense Incongruent - Single Neutral | 11.01 | 29.28 | 101.24 | 0.38 | 1.00 |
| Dense Incongruent - Dual Neutral | -4.74 | 28.87 | 88.88 | -0.16 | 1.00 |
| Dense Incongruent - Dense Neutral | -21.34 | 9.26 | 3.94 | -2.31 | .48 |
| Dense Incongruent - Single Incongruent | 1.78 | 28.61 | 124.53 | 0.06 | 1.00 |

# Appendix I

## Stroop task: Pairwise analysis of EM means of fixed effects' interaction

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Congruent - Single Incongruent | -66.81 | 4.75 | 9971 | -14.07 | < .0001 |
| Single Congruent - Dual Incongruent | -72.89 | 30.85 | 143 | -2.36 | .18 |
| Single Congruent - Dense Incongruent | -50.27 | 31.11 | 137 | -1.62 | .59 |
| Dual Congruent - Single Congruent | 11.42 | 31.00 | 146 | 0.37 | 1.00 |
| Dual Congruent - Dense Congruent | 14.47 | 34.53 | 147 | 0.42 | 1.00 |
| Dual Congruent - Single Incongruent | -55.39 | 30.88 | 144 | -1.79 | .47 |
| Dual Congruent - Dual Incongruent | -61.47 | 5.79 | 9971 | -10.62 | < .0001 |
| Dual Congruent - Dense Incongruent | -38.85 | 34.44 | 145 | -1.13 | .87 |
| Dual Incongruent - Single Incongruent | 6.08 | 30.73 | 141 | 0.20 | 1.00 |
| Dual Incongruent - Dense Incongruent | 22.63 | 34.30 | 143 | 0.66 | .99 |
| Dense Congruent - Single Congruent | -3.04 | 31.22 | 138 | -0.10 | 1.00 |
| Dense Congruent - Dual Incongruent | -75.94 | 34.40 | 145 | -2.21 | .24 |
| Dense Congruent - Dense Incongruent | -53.31 | 5.97 | 9971 | -8.93 | < .0001 |
| Dense Congruent - Single Incongruent | -69.86 | 31.10 | 136 | -2.25 | .23 |
| Dense Incongruent - Single Incongruent | -16.54 | 30.99 | 134 | -0.53 | .99 |

## Appendix J

### Emotional Stroop task: Pairwise analysis of EM means of fixed effects' interaction

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Neutral - Single Negative | 0.08 | 4.94 | 114 | 0.02 | 1.00 |
| Single Neutral - Dual Negative | -19.04 | 28.6` | 140 | -0.67 | 1.00 |
| Single Neutral - Dense Negative | -33.99 | 29.30 | 142 | -1.16 | .96 |
| Single Neutral - Single Positive | -1.04 | 4.92 | 112 | -0.21 | 1.00 |
| Single Neutral - Dual Positive | -24.71 | 28.66 | 141 | -0.86 | .99 |
| Single Neutral - Dense Positive | -40.36 | 29.32 | 143 | -1.38 | .90 |
| Single Negative - Single Positive | -1.11 | 5.46 | 114 | -0.20 | 1.00 |
| Single Negative - Dual Positive | -24.79 | 28.74 | 143 | -0.86 | .99 |
| Single Negative - Dense Positive | -40.43 | 29.40 | 144 | -1.38 | .91 |
| Dual Neutral - Single Neutral | 20.77 | 28.52 | 139 | 0.73 | 1.00 |
| Dual Neutral - Dense Neutral | -7.76 | 31.81 | 138 | -0.24 | 1.00 |
| Dual Neutral - Single Negative | 20.85 | 28.60 | 140 | 0.73 | 1.00 |
| Dual Neutral - Dual Negative | 1.73 | 6.11 | 265 | 0.28 | 1.00 |
| Dual Neutral - Dense Negative | -13.22 | 31.93 | 140 | -0.41 | 1.00 |
| Dual Neutral - Single Positive | 19.74 | 28.59 | 140 | 0.69 | 1.00 |
| Dual Neutral - Dual Positive | -3.93 | 6.09 | 262 | -0.65 | 1.00 |
| Dual Neutral - Dense Positive | -19.58 | 31.95 | 140 | -0.61 | 1.00 |
| Dual Negative - Single Positive | 18.01 | 28.68 | 142 | 0.63 | 1.00 |
| Dual Negative - Dual Positive | -5.67 | 6.74 | 263 | -0.84 | 1.00 |
| Dual Negative - Dense Positive | -21.32 | 32.03 | 142 | -0.67 | 1.00 |
| Dual Positive - Single Positive | 23.68 | 28.73 | 143 | 0.82 | 1.00 |
| Dual Positive - Dense Positive | -15.64 | 32.07 | 143 | -0.49 | 1.00 |
| Dual Negative - Single Negative | 19.12 | 28.69 | 142 | 0.67 | 1.00 |
| Dual Negative - Dense Negative | -14.95 | 32.01 | 141 | -0.47 | 1.00 |
| Dense Neutral - Single Neutral | 28.53 | 29.17 | 140 | 0.98 | .99 |
| Dense Neutral - Single Negative | 28.61 | 29.25 | 139 | 0.98 | .99 |
| Dense Neutral - Dual Negative | 9.49 | 31.89 | 139 | 0.30 | 1.00 |
| Dense Neutral - Dense Negative | -5.46 | 6.25 | 289 | -0.87 | .99 |
| Dense Neutral - Single Positive | 27.50 | 29.24 | 141 | 0.94 | .99 |
| Dense Neutral - Dual Positive | 3.82 | 31.94 | 140 | 0.12 | 1.00 |
| Dense Neutral - Dense Positive | -11.82 | 6.27 | 293 | -1.89 | 0.62 |
| Dense Negative - Single Negative | 34.07 | 29.38 | 144 | 1.16 | 0.96 |
| Dense Negative - Single Positive | 32.96 | 29.337 | 143 | 1.12 | .97 |
| Dense Negative - Dual Positive | 9.28 | 32.05 | 142 | 0.29 | 1.00 |
| Dense Negative - Dense Positive | -6.36 | -6.92 | 292 | -0.92 | .99 |
| Dense Positive - Single Positive | 39.32 | 29.39 | 144 | 1.34 | .92 |

# Appendix K

## Emotional Go/No-go task: Pairwise analysis of EM means of fixed effects' interaction

### *a) LC x Emotion*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Negative - Single Positive | -2.44 | 40.9 | 387 | -0.06 | 1.00 |
| Single Negative - Dual Positive | -16.57 | 45.0 | 284 | -0.37 | 1.00 |
| Single Negative - Dense Positive | 35.23 | 47.9 | 244 | 0.74 | .98 |
| Dual Positive - Single Positive | 14.13 | 31.2 | 101 | 0.45 | 1.00 |
| Dual Negative - Single Negative | 39.40 | 33.1 | 101 | 1.19 | .84 |
| Dual Negative - Dual Positive | 22.83 | 45.1 | 285 | 0.51 | 1.00 |
| Dual Negative - Dense Positive | 74.63 | 47.9 | 245 | 1.56 | .63 |
| Dual Negative - Single Positive | 36.96 | 41.0 | 388 | 0.90 | .95 |
| Dense Positive - Single Positive | -37.67 | 35.1 | 101 | -1.07 | 0.89 |
| Dense Positive - Dual Positive | -51.80 | 39.9 | 101 | -1.30 | .78 |
| Dense Negative - Single Negative | 41.77 | 32.2 | 101 | 1.30 | .78 |
| Dense Negative - Dual Negative | 2.38 | 32.2 | 102 | 0.07 | 1.00 |
| Dense Negative - Single Positive | 39.33 | 40.2 | 415 | 0.98 | .92 |
| Dense Negative - Dual Positive | 25.20 | 44.4 | 296 | 0.57 | .99 |
| Dense Negative - Dense Positive | 77.01 | 47.3 | 251 | 1.63 | .58 |

### *b) LC x Stimulus gender*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Female - Dense Male | -7.17 | 24.04 | 105 | -0.30 | 1.00 |
| Single Female - Dual Male | -31.72 | 22.96 | 105 | -1.38 | .74 |
| Single Female - Single Male | -3.82 | 4.03 | 5837 | -0.95 | .93 |
| Dual Female - Single Female | 2563 | 22.95 | 105 | 1.12 | .87 |
| Dual Female - Dense Male | 18.46 | 25.88 | 105 | 0.71 | .98 |
| Dual Female - Dual Male | -6.09 | 5.06 | 5837 | 0.95 | .84 |
| Dual Female - Single Male | 21.81 | 22.95 | 105 | 0.95 | .93 |
| Dual Male - Single Male | 27.90 | 22.96 | 105 | 1.22 | .83 |
| Dense Female - Dual Female | -24.88 | 25.88 | 105 | -0.96 | .93 |
| Dense Female - Single Female | 0.75 | 24.04 | 105 | 0.03 | 1.00 |
| Dense Female - Dense Male | -6.42 | 5.19 | 5838 | -1.24 | .82 |
| Dense Female - Dual Male | -30.97 | 25.88 | 105 | -1.20 | .84 |
| Dense Female - Single Male | -3.07 | 24.05 | 105 | -0.13 | 1.00 |
| Dense Male - Dual Male | -24.55 | 25.88 | 105 | -0.95 | .93 |
| Dense Male - Single Male | 3.35 | 24.04 | 105 | 0.14 | 1.00 |

### *c) LC x Emotion x Stimulus gender*

| Contrast | Estimate | SE | df | t-ratio | p-value |
|---|---|---|---|---|---|
| Single Female Positive - Single Male Positive | -3.82 | 4.03 | 5837 | -0.95 | 1.00 |
| Single Female Positive - Dual Male Positive | -19.09 | 31.33 | 103 | -0.61 | 1.00 |
| Single Female Positive - Dense Male Positive | 32.55 | 35.30 | 102 | 0.92 | 1.00 |
| Single Female Negative - Single Male Negative | -3.82 | 4.03 | 5837 | -0.95 | 1.00 |
| Single Female Negative - Dual Male Negative | -44.35 | 33.24 | 103 | -1.33 | 0.97 |
| Single Female Negative - Dense Male Negative | -46.89 | 32.32 | 103 | -1.45 | 0.95 |

| | | | | | |
|---|---|---|---|---|---|
| Single Female Negative - Single Female Positive | -2.44 | 40.91 | 387 | -0.06 | 1.00 |
| Single Female Negative - Dual Female Positive | -15.44 | 45.14 | 287 | -0.34 | 1.00 |
| Single Female Negative - Dense Female Positive | 36.53 | 47.98 | 246 | 0.76 | 1.00 |
| Single Female Negative - Single Male Positive | -6.26 | 41.11 | 394 | -0.15 | 1.00 |
| Single Female Negative - Dual Male Positive | -21.53 | 45.14 | 287 | -0.48 | 1.00 |
| Single Female Negative - Dense Male Positive | 30.11 | 47.98 | 246 | 0.63 | 1.00 |
| Single Male Negative - Single Female Positive | 1.38 | 41.11 | 394 | 0.03 | 1.00 |
| Single Male Negative - Dual Female Positive | -11.61 | 45.14 | 287 | -0.26 | 1.00 |
| Single Male Negative - Dense Female Positive | 40.35 | 47.98 | 246 | 0.84 | 1.00 |
| Single Male Negative - Single Male Positive | 2.44 | 40.91 | 387 | -0.06 | 1.00 |
| Single Male Negative - Dual Male Positive | 17.70 | 45.14 | 287 | -0.39 | 1.00 |
| Single Male Negative - Dense Male Positive | 33.94 | 47.98 | 246 | 0.71 | 1.00 |
| Dual Female Positive - Single Male Positive | 9.17 | 31.33 | 103 | 0.29 | 1.00 |
| Dual Female Positive - Dual Male Positive | -6.09 | 5.06 | 5837 | -1.20 | 1.00 |
| Dual Female Positive - Dense Male Positive | 45.55 | 40.02 | 102 | 1.14 | .99 |
| Dual Female Positive - Single Female Positive | 13.00 | 31.33 | 103 | 0.42 | 1.00 |
| Dual Female Negative - Single Female Negative | 38.26 | 33.24 | 103 | 1.15 | .99 |
| Dual Female Negative - Single Male Negative | 34.44 | 33.24 | 103 | 1.04 | 1.00 |
| Dual Female Negative - Dual Male Negative | -6.09 | 5.06 | 5837 | -1.20 | 1.00 |
| Dual Female Negative - Dense Male Negative | -8.63 | 32.42 | 104 | -0.27 | 1.00 |
| Dual Female Negative - Single Female Positive | 35.82 | 41.08 | 393 | 0.87 | 1.00 |
| Dual Female Negative - Dual Female Positive | 22.83 | 45.06 | 285 | 0.51 | 1.00 |
| Dual Female Negative - Dense Female Positive | 74.79 | 48.04 | 247 | 1.56 | .92 |
| Dual Female Negative - Single Male Positive | 32.00 | 41.08 | 393 | 0.78 | 1.00 |
| Dual Female Negative - Dual Male Positive | 16.74 | 45.35 | 292 | 0.49 | 1.00 |
| Dual Female Negative - Dense Male Positive | 68.38 | 48.04 | 247 | 1.42 | .96 |
| Dual Male Positive - Single Male Positive | 15.26 | 31.34 | 103 | 0.49 | 1.00 |
| Dual Male Negative - Single Female Positive | 41.91 | 41.09 | 393 | 1.02 | 1.00 |
| Dual Male Negative - Dual Female Positive | 28.92 | 45.34 | 292 | 0.64 | 1.00 |
| Dual Male Negative - Dense Female Positive | 80.88 | 48.04 | 247 | 1.68 | .87 |
| Dual Male Negative - Single Male Positive | 38.09 | 41.09 | 393 | 0.93 | 1.00 |
| Dual Male Negative - Dual Male Positive | 22.83 | 45.06 | 285 | 0.51 | 1.00 |
| Dual Male Negative - Dense Male Positive | 74.47 | 48.04 | 247 | 1.55 | .92 |
| Dual Male Negative - Single Male Negative | 40.53 | 33.24 | 103 | 1.22 | .99 |
| Dense Female Positive - Single Female Positive | -38.97 | 35.30 | 102 | -1.10 | 0.99 |
| Dense Female Positive - Dual Female Positive | -51.97 | 40.02 | 102 | -1.30 | .98 |
| Dense Female Positive - Single Male Positive | -42.79 | 35.30 | 102 | -1.21 | .99 |
| Dense Female Positive - Dual Male Positive | -58.06 | 40.03 | 102 | -1.45 | .95 |
| Dense Female Positive - Dense Male Positive | -6.42 | 5.19 | 5838 | -1.24 | .99 |
| Dense Female Negative - Single Female Negative | 40.48 | 32.32 | 103 | 1.25 | .98 |
| Dense Female Negative - Dual Female Negative | 2.21 | 32.42 | 104 | 0.07 | 1.00 |
| Dense Female Negative - Single Male Negative | 36.65 | 32.32 | 103 | 1.13 | .99 |
| Dense Female Negative - Dual Male Negative | -3.88 | 32.42 | 104 | -0.12 | 1.00 |
| Dense Female Negative - Dense Male Negative | -6.42 | 5.19 | 5838 | -1.24 | .99 |
| Dense Female Negative - Single Female Positive | 38.04 | 40.34 | 420 | 0.94 | 1.00 |
| Dense Female Negative - Dual Female Positive | 25.04 | 44.53 | 300 | 0.56 | 1.00 |
| Dense Female Negative - Dense Female Positive | 77.01 | 47.27 | 251 | 1.63 | .90 |
| Dense Female Negative - Single Male Positive | 34.21 | 40.34 | 420 | 0.85 | 1.00 |
| Dense Female Negative - Dual Male Positive | 18.95 | 44.54 | 300 | 0.43 | 1.00 |
| Dense Female Negative - Dense Male Positive | 70.59 | 47.55 | 257 | 1.49 | .94 |
| Dense Male Positive - Single Male Positive | -36.38 | 35.30 | 102 | -1.03 | 1.00 |
| Dense Male Positive - Dual Male Positive | -51.64 | 40.02 | 102 | -1.29 | .99 |
| Dense Male Negative - Single Male Negative | 43.07 | 32.33 | 103 | 1.33 | .97 |
| Dense Male Negative - Dual Male Negative | 2.54 | 32.42 | 104 | 0.08 | 1.00 |
| Dense Male Negative - Single Female Positive | 44.45 | 40.35 | 420 | 1.10 | .99 |
| Dense Male Negative - Dual Female Positive | 31.46 | 44.53 | 300 | 0.71 | 1.00 |

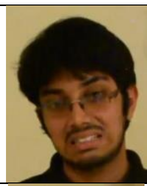
| | | | | | |
|---|---|---|---|---|---|
| Dense Male Negative - Dense Female Positive | 83.42 | 47.56 | 257 | 1.76 | .84 |
| Dense Male Negative - Single Male Positive | 40.63 | 40.35 | 420 | 1.01 | 1.00 |
| Dense Male Negative - Dual Male Positive | 25.37 | 44.54 | 300 | 0.57 | 1.00 |
| Dense Male Negative - Dense Male Positive | 77.01 | 47.27 | 251 | 1.63 | .90 |

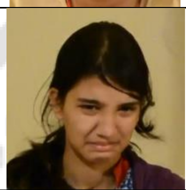
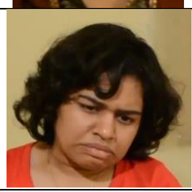
# Appendix L

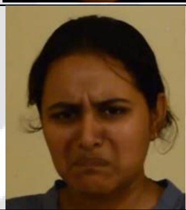
## Emotion faces used for Emotion Go/No-go task

| Gender | Emotion | Image |
|---|---|---|
| Male | Positive |  |
| Male | Positive |  |
| Male | Positive |  |
| Male | Positive |  |
| Male | Positive |  |
| Male | Positive |  |
| Male | Positive |  |

| | | |
|---|---|---|
| Male | Positive |  |
| Male | Positive |  |
| Male | Positive |  |
| Male | Negative |  |
| Male | Negative |  |
| Male | Negative |  |
| Male | Negative |  |
| Male | Negative |  |

| | | |
|---|---|---|
| Male | Negative |  |
| Male | Negative |  |
| Male | Negative |  |
| Male | Negative |  |
| Male | Negative |  |
| Female | Positive |  |
| Female | Positive |  |
| Female | Positive |  |
| Female | Positive |  |

| | | |
|---|---|---|
| Female | Positive |  |
| Female | Positive |  |
| Female | Positive |  |
| Female | Positive |  |
| Female | Positive |  |
| Female | Positive |  |
| Female | Negative |  |
| Female | Negative |  |
| Female | Negative |  |

| | | |
|---|---|---|
| Female | Negative |  |
| Female | Negative |  |
| Female | Negative |  |
| Female | Negative |  |
| Female | Negative |  |
| Female | Negative |  |
| Female | Negative |  |