Design and Evaluation of Naamya: A Bend Gesture-based Tool to Draw Primitive Geometric Shapes for Users with Blindness or Low Vision

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by

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CERTIFICATE

This is to certify that the thesis entitled "**Design and Evaluation of Naamya: A Bend Gesture-based Tool to Draw Primitive Geometric Shapes for Users with Blindness or Low Vision**" submitted by Mr. Pranjal Protim Borah to the Indian Institute of Technology Guwahati, for the award of the degree of Doctor of Philosophy in Design is a record of bonafide research work carried out by him under my supervision and guidance. This thesis work, in my opinion, has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy. The results contained in this thesis have not been submitted in part or full to any other University or Institute for an award of any degree or diploma.

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STATEMENT

I do hereby declare that the matter embodied in this thesis entitled "Design and Evaluation of Naamya: A Bend Gesture-based Tool to Draw Primitive Geometric Shapes for Users with Blindness or Low Vision" is the result of investigations carried out by me under the supervision of Dr. Keyur Babulal Sorathia at the Department of Design, Indian Institute of Technology Guwahati, Guwahati, Assam, India.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

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Abstract

With enhanced tactile perception, users with blindness or low vision practice tactile tools as learning aids, such as geoboards, pegboards, raised-line drawing boards, and heat-sensitive swell papers. However, this tactile drawing process is time-consuming, and the tactile drawing tools present several challenges and limitations. Maintaining accurate progress in drawing with tactile drawing tools becomes challenging due to difficulties in following an intended direction, difficulties in performing an intended change in direction, adverse effects of unknown orientation and rotation of the tool, wrong perception of spatial direction, and distracting manual effort during peg insertion. These tactile drawing tools also have limitations in terms of providing additional feedback, the fix-sized physical grid of the drawing board, and additional functionalities such as erasing, modifying, and storing the drawings. Today's education system is taking advantage of digital solutions. Users with visual impairment or blindness can also interact with these digital devices through the keyboard, mouse, touchscreen, and screen readers. While keyboard-based interaction offers essential tactile feedback during the interaction, it limits the mapping to real-world spatial directions. On the other hand, touch gestures can be mapped to real-world spatial directions. However, these touch-based interactions lack the innate tactile feedback of active touch during interaction with touchscreen devices. Together keyboard and touch-based interaction are limited in their ability to provide an input interaction modality that is accompanied by both inherent tactile feedback and association with spatial directional cues. This makes accurate movement in any spatial direction difficult when using these input modalities for digital drawing on a handheld device without relying on additional feedback.

To overcome these limitations, we took the opportunity to use deformation gestures on a smartphone-sized flexible handheld device. Performing deformation gestures offers better mapping with different spatial directional cues and the most significant advantage is its

innate tactile and kinesthetic feedback during input. With a deformable user interface, the user can provide discrete and continuous input by manipulating the physical form factor of the device. A user can provide a large set of deformation gesture-based inputs by performing different types of deformations, such as bending, rolling, folding, twisting, and squeezing the device at different locations and directions of the device with multiple sizes, angles, and speeds of deformation. Out of different types of deformations, bending the device is majorly investigated in the literature for handheld devices and also found to be easy to learn and perform by users with blindness. These bend gestures are found to be useful for visually impaired users and can enable eyes-free interaction by sighted users, making the gesture space more inclusive for a diverse set of users and suitable for different contexts of use. This bend gesture-based interaction is selected for further investigation to utilize it as the primary input modality for the digital drawing tool (Naamya) designed in this research work. We selected smartphone-sized handheld devices for designing the gesture space, considering smartphones to be the most commonly used and carried digital devices by blind users. In this thesis work, we conducted six studies where the first and second studies aimed to understand the existing drawing tools and strategies used for drawing. The third and fourth studies aimed to design the preferred bend gesture space with additional descriptors and bend gesture completion strategies. The fifth and sixth studies aimed to design the digital drawing tool (Naamya), followed by its evaluation compared to a pegboard-based drawing tool (Taylor Arithmetic Slate).

In the first study, we conducted an interview-based retrospective study with students and teachers with blindness or low vision in the Indian context. This study aimed to understand the experience of students and teachers in learning and creating mathematical diagrams, the use of existing mathematical drawing tools, and the need and scope for improvement of drawing tools through technological interventions. The key findings of this study that helped our subsequent studies are that students usually learn only primitive geometric shapes at school. They often use different tools for learning shapes containing straight lines and circular paths, and the pegboard-based tool (Taylor Arithmetic Slate) is the most commonly used drawing tool for primitive geometric shapes containing straight lines. We also found that students often take help from their sighted family members and friends during drawing and prefer digital tools with tactile and verbal feedback. In the second study, we conducted

an observational study with students with blindness or low vision. This study aimed to understand the process of drawing primitive geometric shapes (triangles and rectangles) and reading compound shapes (containing a triangle and a rectangle) to help design digital drawing tools that correspond to the user's mental model of using existing tactile drawing tools. We identified a set of validation strategies for drawing primitive geometric shapes and shape identification techniques for reading which were used by the participants for error prevention and recovery. This understanding of the drawing and reading process, including the strategies, helped us propose a set of functions for designing a digital tool that corresponds to the user's existing mental model.

In the next phase, we conducted the third study to design the bend gesture space considering two basic descriptors (location and direction) and two additional descriptors (size and angle) of bend gestures. We conducted the fourth study to identify user-preferred gesture completion strategies that have the potential to overcome unwanted and unintended input. Considering the findings from the first study, which evidence that blind and low vision (BLV) students often take help from the sighted, we included both BLV and sighted users during the third and fourth studies. The reason to include sighted users is the potential need to assist users with blindness or low vision during teaching and training. However, the contributions of this thesis are focused on the BLV user group only. Accordingly, the findings and observations concerning only the BLV user group are taken forward for the subsequent studies reported in this research work. The key findings of the third study that helped our subsequent studies are that both participant groups reported higher preferences for two magnitude levels of size and angle of bend at all four corners and for two magnitude levels of only size at the top and bottom sides of the device in portrait orientation. The BLV participants preferred both upward and downward bend directions, while the sighted participants preferred only upward. We also found that size-based gestures need less continuous attention and have reduced risk of potential error while bending the device. In addition, according to both participant groups, differentiation of two magnitude levels of size is easier than angle differentiation and offers higher confidence during input. Later in the fourth study, we identified four (On-Hold, On-Release, On-Relax, and On-Double-Bend) and three (On-Hold, On-Second-Bend, and On-Quick-Relax) unique strategies for discrete and continuous inputs, respectively.

In the next phase, we conducted the fifth study to design the bend gesture-based digital

drawing tool named Naamya. The word Nāmya (pronounced as Naamya) is a Sanskrit word that means bendable, pliant, pliable, or flexible. We utilized a participatory design approach to design Naamya by involving students with visual impairment or blindness and their teachers in the design process. This study aimed to finalise the required feedback modalities of the bend gesture-based drawing tool and the tool's basic and advanced functions. This study also aimed to map these functions with bend gestures and to finalise the bend gesture completion strategies to trigger associated functions. As the outcome of this study, Naamya, the bend gesture-based smartphone-sized digital drawing tool, is designed. Finally, in the sixth study, we investigated the effectiveness of Naamya compared to a pegboard-based drawing tool (Taylor Arithmetic Slate) and found them to be equally effective in drawing primitive geometric shapes containing straight lines. Naamya also leads to significantly less number of slips during drawing. Most notably, the perceived inherent tactile and kinesthetic feedback of bend gestures and the spatial directions associated with the bend gestures offer several advantages to Naamya. Naamya encourages to continue practising drawings, offers confidence in correctly drawing straight lines, offers confidence in selecting the next intended hole correctly, offers ease of perceiving the change in the direction of progress, makes the drawing task error-proof to the wrong next-hole selection, and enables correct navigation. We also found no statistically significant difference between the tools in terms of ease of use, ease of learning, and ease of building a mental spatial layout. This thesis work laid out four major contributions. The contributions of this thesis will help Human-computer Interaction (HCI) researchers and User Experience (UX) designers design drawing tools and bend gesture-based interactions for users with blindness or low vision.

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List of Abbreviations

The abbreviations used in this thesis are listed below in alphabetical order:

2D: Two Dimensional

3D: Three Dimensional

AS: Agreement Scores

BD: Bend-downward

BLC: Bottom-left-corner

BLV: Blind and Low Vision

BRC: Bottom-right-corner

BS: Bottom-side

BU: Bend-upward

EVA: Ethylene-vinyl Acetate

GSK: Graph SKetching

GUI: Graphical User Interface

HCD: Human-centered Design

HCI: Human-computer Interaction

IC2D: Integrated Communication 2 Draw

ICTD: Information and Communication Technologies for Development

IFIP: International Federation for Information Processing

RQ: Research Question

STEM: Science, Technology, Engineering, and Mathematics

TLC: Top-left-corner

TPU: Thermoplastic Polyurethane

TRC: Top-right-corner

TS: Top-side

TTS: Text to Speech

TUI: Tangible User Interface

UX: User Experience

Chapter 1

Introduction

1.1 Context of Research and Motivation

According to a global estimate by the Vision Loss Expert Group (Bourne et al., 2017), worldwide, 216·6 million people had moderate to severe visual impairment and there were 36 million people with blindness in 2015. Of this estimated population, the largest group (11·7 million) resided in the South Asia region. In this region, India is one of the countries that have a major contribution to the global population of people with visual impairment (Malhotra et al., 2018). According to the National Blindness and Visual Impairment Survey 2015-2019 India, there are 4.8 million people with blindness in India (National Programme for Control of Blindness & Visual Impairment, 2019; Directorate General of Health Services, 2020). As reported in the Indian statistical profile in 2021 on persons with disabilities (Divyangjan) (National Handicapped Finance and Development, 2021) based on the available data (Census of India, 2011), out of the total disability population, the disability in seeing is 19%, which stands next to the largest (20%) population of persons with disability in movement, and 19% population of persons with disability in hearing.

Out of the entire population of children with disability in the age group 5-19 years in India, 61% are attending an educational institution (National Handicapped Finance and Development, 2021). With the help of the increasing use of assistive technology, the social and economic inclusion of people with blindness or low vision has also increased (Pal & Lakshmanan, 2012). Considering the employment of the age-wise eligible candidates and future employment of the lower age group, it is also crucial to make them academically

eligible. In this context, to appear for a job opportunity, they must learn and understand the necessary components of the academic curriculum. To comprehend the curriculum's content, students who are blind or have low vision depend on braille books, tactile tools, recorded audio sessions and audiobooks (Wersényi, 2009; Velázquez, 2010; Vashistha, Brady, Thies, & Cutrell, 2014).

Learning and teaching the visually demanding components of the curriculum often becomes challenging and time-consuming (Klingenberg, 2007) and demands more effort and time from both students and teachers. For this component, the students take advantage of their superior tactile acuity (Goldreich & Kanics, 2003, 2006) and use tactile tools as learning aids, such as geoboards, pegboards, raised-line drawing boards (Zhao et al., 2021; Fernando & Ohene-Djan, 2021), and heat-sensitive swell papers (Kamel & Landay, 1999). While using raised-line drawing boards and heat-sensitive swell papers offers better tactile exploration during reading, users often have to use additional tools to draw straight lines and circular paths as these tools offer freehand drawing opportunities. Moreover, unknown orientation and rotation of the drawing board during drawing may also influence accurate progress in drawing and accurate change in the direction during drawing (Appelle & Gravetter, 1985; Heller, 1992). Due to the inability or difficulty of erasing and modifying the drawings on these tools, the entire process of creating complex diagrams often necessitates extra caution and eventually becomes more challenging and time-consuming. This slow and serial information acquisition also affects haptic exploration (Heller, Calcaterra, Burson, & Tyler, 1996; Cecchetto & Lawson, 2015). Moreover, the tactile property of raised-line drawing sheets becomes less effective with extensive use creating challenges in storing them for future use. In contrast, one major advantage of using geoboards and pegboards is the grid which offers additional tactile feedback to assist users in easily drawing straight lines and circular paths following the predefined grid. However, often different geoboards and pegboards are used to draw straight and circular paths. These grid-based tools offer a better opportunity to maintain accurate progress in drawing and perform an accurate change in the direction during drawing. However, closely placed nails of geoboards could lead to a wrong perception of spatial direction during tactile exploration of the target nail, and the act of manually attaching the rubber bands leads to errors during drawing. Similarly, closely placed holes of pegboards could also lead to a wrong perception of spatial direction during tactile

exploration of the target hole, and the act of manually picking up the pegs and inserting them in the pegboard leads to errors during drawing (Borah & Sorathia, 2019a). Moreover, unknown orientation and rotation of the drawing board during drawing could also contribute to the wrong perception and selection of nails and holes on these drawing boards. Although the tactile grids of nails of geoboards and holes of pegboards offer ease of drawing, the scope of the drawing area is also restricted by this physical grid on these tools. Furthermore, apart from tactile feedback during drawing, these analogue tactile drawing tools have limitations in providing additional feedback during drawing for collaborative work and storing the drawing for reuse and transfer. These limitations of the drawing tools make it difficult to learn and practise basic concepts such as geometric shapes, coordinate geometry, and graphs.

Such challenges in learning tools combined with limited learning opportunities result in more difficulty in those visually demanding components of the curriculum, and in due course, it leads to reduced interest and expertise in the related subjects, which demands this prior basic knowledge (Klingenberg, 2007). One such component is learning mathematical diagrams. Learning and creating mathematical diagrams starts at the primary school level, where students with blindness or low vision learn basic geometric concepts. These basic concepts, including shape, size, dimension, and spatial orientation, are also a part of primary education for sighted students (Sherard, 1981). Learning these concepts could also be helpful for blind and low vision (BLV) students in their academic work and day-to-day life (Smith, 2006). According to Brooks, 2009, "drawing is both a means of communication as well as a problem-solving tool", and individuals with blindness or low vision could also benefit from drawing (Kennedy, 1997; Hospitál, 2017). In academic work, learning these concepts enables them to draw and read block diagrams, node-link diagrams, graphs, and charts, to name a few. This learning is not only for students who want to pursue higher education in STEM (Science, Technology, Engineering, and Mathematics) but also helps students develop their mental space representation (Thinus-Blanc & Gaunet, 1997). This mental spatial representation is beneficial in performing day-to-day work such as measuring the distance between objects, establishing spatial relations of an object with respect to another, avoiding collision and navigation (Sherard, 1981; Rouzier, Hennion, Segovia, & Chêne, 2004; Smith, 2006). Collectively, learning these basic concepts could enable individuals with blindness or low vision to apply these concepts independently without sighted assistance.

In the Indian context, students commonly use the Taylor Arithmetic Slate for learning geometric drawings, which is a tool for arithmetic calculation (Borah & Sorathia, 2019a). During our initial visits to a school for visually impaired students, we saw a couple of 18-20 years old students struggling to draw squares, rectangles, and triangles on pegboards and wooden geoboards. The frequent hand movements to find the appropriate holes to insert the pegs or select the nails to attach the rubber bands showcase the level of frustration experienced by the students during the drawing process. Although drawing by touching the pegboard and geoboard is a tactile learning process, overwhelming tactile stimuli could contribute to confusion (Zebehazy & Wilton, 2014; Phutane et al., 2022), for instance, touching several pegs, holes and nails while drawing. Students are less interested and enthusiastic in using complex tactile graphics (Phutane et al., 2022) due to the increased challenges associated with the increased complexity of the tactile graphics (Zebehazy & Wilton, 2014). These difficulties could also lead to reduced interest in the subject and even discontinuing the subject in the future. It has also been reported in the literature (Taraporevala, 2016) that out of the visually impaired children who attend school in India, very few continue with Science and Mathematics beyond the seventh grade. Also, the lack of motivation among the students to learn mathematics and science (Dey, Vidhya, Bhushan, Neerukonda, & Prakash, 2019; Parthasarathy, Dey, & Gupta, 2021) could be an outcome of the challenges associated with tactile graphics and limitations in existing analogue drawing tools which are commonly used during early stages of learning basic concepts such as primitive geometric shapes. As a result, later, they find other related topics, such as geometry, coordinate geometry and graphs, difficult to understand. These difficulties in learning the basic concepts usually lead to dislike mathematics (Klingenberg, 2007) and gradually discontinue in the future (Taraporevala, 2016). Difficulty in learning these mathematical concepts eventually affects the performance in Mathematics and gradually other subjects such as Science, Physics, and Chemistry (Sahasrabudhe & Palvia, 2013). Furthermore, apart from subjects related to mathematics, since the basic concepts are not understood effectively, it creates difficulty in any drawing task, which is essential in writing reports and articles. This also creates difficulty in reading documents which contain visual representations of information such as graphs and node-link diagrams (Sherard, 1981; Kennedy, 1997; Rouzier et al., 2004; Hospitál, 2017). Moreover, according to Sherard, 1981,

comprehension of geometric concepts is also required to develop fundamental map-reading skills. In this context, a digital tool to learn basic geometric concepts that resemble the tactile drawing process could enable users to overcome the challenges of existing drawing tools.

Today's education system is taking advantage of digital solutions, and within this context, a digital tool that corresponds to the user's mental model of using pegboard-based tactile drawing tools has the potential to address the challenges and limitations of analogue tactile drawing tools. Users with visual impairment or blindness can also interact with these digital devices with the help of a keyboard, mouse, touchscreen, and screen readers. Although conventional keyboard-based interaction offers essential tactile feedback during the interaction (Hoggan, Brewster, & Johnston, 2008), unlike dynamic hand gesture-based input (Freeman & Roth, 1995) and single-finger uni-stroke gestures on a physical keyboard (H. Zhang & Li, 2014), pressing the keys with multiple fingers limits the mapping to real-world spatial directions perceived through finger movement. Users can only perceive the hand and finger movements required to position the fingers that match the keys' spatial layout. Software keyboards also fail to offer tactile affordances (Hoggan et al., 2008) or tactile feedback for eyes-free interaction (Romero, Frey, Southern, & Abowd, 2011). While interacting with a digital pen or a mouse allows both tactile feedback and association with spatial directions, it requires additional tools or guiding feedback to follow desired paths (straight and circular) during drawing (Kurze, 1996; Yu, Kangas, & Brewster, 2003; Calder, Cohen, Lanzoni, & Xu, 2006). On the other hand, touch gestures can be mapped to real-world spatial directions. However, these touch gesture-based interactions lack the innate tactile feedback of active touch during interaction with the touchpad or touchscreen devices. This leads to challenges of accurate movement in any spatial direction without additional feedback (Oh, Kane, & Findlater, 2013). This indicates the need to investigate an interaction modality that provides innate tactile feedback and that is associated with real-world spatial directions. In addition, the touchscreen-based interaction is visually demanding (Oliveira, Guerreiro, Nicolau, Jorge, & Gonçalves, 2011), and the lack of physical and tactile buttons make it even more challenging (Oliveira et al., 2011; Kane, Morris, & Wobbrock, 2013). Users with visual impairment or blindness can use these touchscreen devices with the help of screen readers such as Android's Talkback and iOS' VoiceOver (Wersényi, 2009; Rodrigues, Montague, Nicolau, & Guerreiro, 2015) along with non-speech sound feedback such as

musical tones, earcons, everyday sounds, synthesized sounds (Brewster, 1994; Sakhardande, Joshi, Jadhav, & Joshi, 2019) and vibrotactile feedback (Nishino et al., 2011; Azenkot, Ladner, & Wobbrock, 2011). This vibrotactile feedback can be provided in such a way that it can provide the perception of both active and passive touch (Choi & Kuchenbecker, 2012). However, active movements of the user's hand might impair the tactile perception provided through vibrotactile feedback (Post, Zompa, & Chapman, 1994). On the other hand, active touch by the user has higher perceptual performance (Lederman & Klatzky, 1987). Also, according to literature, haptic exploration typically results in significantly better memory than passive tactile stimulation (Gallace & Spence, 2020). This also indicates the opportunity to investigate an interaction modality that provides innate tactile feedback. In this context, deformation gesture-based interaction with its innate tactile and kinaesthetic feedback and its association with spatial directional cues (Ahmaniemi, Kildal, & Haveri, 2014; Borah, Seth, & Sorathia, 2021) provides an opportunity to investigate it as a novel input interaction modality for a digital drawing tool for students with blindness or low vision.

With the advancement in flexible displays and soft electronics, deformable devices are the most promising next-generation technology (Nathan et al., 2012; Boem & Troiano, 2019; Zhou, Zhang, Liu, & Huang, 2021; Wu, Ma, Zheng, & Ramakrishna, 2021; Li & Lim, 2022; Z. Xu, Li, Li, Gao, & Chen, 2022; D. W. Kim et al., 2023) that enables the potential of human-machine interfacing through deformable devices (Tao et al., 2022). Researchers have explored different deformable handheld devices (Schwesig, Poupyrev, & Mori, 2003; Holman, Vertegaal, Altosaar, Troje, & Johns, 2005; Steimle, Jordt, & Maes, 2013; Ernst, Swan, Cheung, & Girouard, 2017; van Oosterhout & Hoggan, 2021) and investigated the interaction space through the deformation-based gestures (Harrison, Fishkin, Gujar, Mochon, & Want, 1998; Schwesig et al., 2003; Schwesig, Poupyrev, & Mori, 2004). With a deformable user interface, the user can provide both discrete and continuous input by manipulating the physical form factor of the device (Schwesig et al., 2004). A user can provide a large set of input by performing different types of deformation such as rolling, folding, twisting, squeezing, and bending the device (S. S. Lee et al., 2010; Kildal, Paasovaara, & Aaltonen, 2012). This gesture space can be further extended by performing the deformation at different locations and directions of the device with multiple sizes, angles, and speeds of deformation (Warren, Lo, Vadgama, & Girouard, 2013). One of the major

advantages of this input technique is its inherent tactile and kinesthetic feedback (Wightman, Ginn, & Vertegaal, 2011) resulting from the applied force in performing the gestures (Kildal, 2012). This innate feedback enables eyes-free interaction with deformable user interfaces (Cheung, Eady, & Girouard, 2017). As a consequence, users with blindness or visual impairment also found deformation gestures to be easy to learn and perform (Ernst et al., 2017). This makes the deformation-based gesture space more inclusive for a diverse set of users and suitable for multiple contexts of use. Deformation gestures also allow users to associate the gestures with one or multiple spatial directions, making gesture action mapping more natural for actions associated with spatial directions (Borah, Seth, & Sorathia, 2021). Inclusiveness and accessibility of an interactive digital product is often the last step taken into account (Kelly et al., 2007; Oswal, 2014). We also believe that it is never too early to investigate the potential of emerging technologies, which is inspired by the viewpoint of Kildal et al., 2012, which states that the development of deformable user interface design does not have to wait until all the necessary technologies to be ready. With this set of motivations, we took the opportunity to investigate the scope for deformation gestures in this research work.

Gestures performed by bending the flexible device are commonly investigated types of deformation in the existing literature (Lahey, Girouard, Burleson, & Vertegaal, 2011; Wightman et al., 2011; Kildal & Wilson, 2012; Steimle et al., 2013; Ahmaniemi et al., 2014; Strohmeier, Burstyn, Carrascal, Levesque, & Vertegaal, 2016; Maqsood, Chiasson, & Girouard, 2016; Fares, Cheung, & Girouard, 2017; Lo & Girouard, 2017; Ernst et al., 2017; Faustino, Nabil, & Girouard, 2020) and found to be effective and enjoyable (Schwesig et al., 2004). Bend gestures are found to be easy to learn and perform by users with blindness (Ernst et al., 2017) and strongly preferred by sighted users (Warren et al., 2013). Participants with no prior experience with flexible devices also found these gestures to be effortless (Lo & Girouard, 2017). Considering these factors, we used bending as the primary type of deformation in this research work. Moreover, since smartphones are one of the most frequently utilized and carried digital devices by users with blindness (Kane, Jayant, Wobbrock, & Ladner, 2009), we found smartphone-sized devices as one of the best choices for exploring their potential as a learning aid. In this context, we took the opportunity to investigate the potential of bend gestures as the primary input modality of a smartphone-sized

handheld digital drawing tool for users with blindness or low vision.

While learning and practising basic geometric drawings is an essential part of the curriculum, the existing tactile drawing tools present a number of challenges and limitations. Maintaining accurate progress in drawing with tactile drawing tools becomes challenging due to difficulties in following an intended direction, difficulties in performing an intended change in direction, adverse effects of unknown orientation and rotation of the tool, wrong perception of spatial direction, and distracting manual effort during peg insertion. These tactile drawing tools also have limitations in terms of providing additional feedback, the fix-sized physical grid of the drawing board, and additional functionalities such as erasing, modifying, and storing the drawings. In the meantime, keyboard and touch-based interactions are limited in their ability to provide an input interaction modality that is accompanied by both inherent tactile feedback and association with spatial directional cues. To overcome the challenges and limitations of tactile drawing tools this thesis aims to investigate the potential of bend gestures as the primary input modality of a digital tool for drawing primitive geometric shapes by users with blindness or low vision.

1.2 Research Questions

This research aims to investigate the potential of bend gestures as the primary input modality of a digital drawing tool that corresponds to the user's existing mental model. We formulated six research questions (RQ) that are presented in the following subsections.

RQ 1: What existing tools and strategies are followed by blind and low vision (BLV) users to draw primitive geometric shapes?

RQ 2: How should the bend gesture space be designed using additional descriptors of bend (size and angle) considering the BLV user group's performance and preference?

RQ 3: What are the preferred bend gesture completion strategies of the BLV user group to provide discrete and continuous input to reduce unwanted or unintended input?

RQ 4: How can the bend gestures be used to design a geometric shape drawing tool that corresponds to the user's existing mental model?

RQ 5: Does a bend gesture-based geometric shape drawing tool enable BLV users to draw primitive geometric shapes effectively compared to the existing drawing tool?

1.3 An Overview of the Research Methodology

This thesis follows a human-centered design (HCD) approach to design a bend gesture-based geometric shape drawing tool for students with blindness or low vision. The human-centered design approach starts with understanding people's needs to propose design solutions (Norman & Draper, 1986; Giacomin, 2014; Harte et al., 2017). ISO 9241-210 (ISO, 2019) describes HCD as an "approach to interactive systems development that aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques.". In order to accomplish this goal by using a human-centered design approach, this research seeks to plan and execute a series of user studies involving students with blindness or low vision and their teachers. This thesis work has been conducted with formal approval from the Institute Human Ethics Committee of the Indian Institute of Technology Guwahati, India. For each study reported in this thesis, participants have given informed consent to participate in respective research work voluntarily. We used the purposive sampling technique considering its efficiency and robustness reported in the literature (Etikan, Musa, & Alkassim, 2016) with an aim to achieve a homogeneous group of participants as a sample group. According to the *Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018, for individuals with disability due to visual impairment, the percentage of impairment could range from 20% to 100% after the best correction of the eyes. This range is divided into four disability categories, where 20% is Category I, 30% is Category II (One eyed person), 40% to 80% is Category III (low vision), and 90% to 100% is Category IV (Blindness). Participants selected for this thesis work have a percentage of impairment of 70% or more, which includes individuals with severe low vision to blindness according to the literature (Monga, Parwal, Rohatgi, & Dhaliwal, 2009; *Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018). In this thesis, we referred to these participants as participants with blindness or low vision as well as blind and low vision (BLV) participants. This 70% impairment means a person with the best corrected better eye is less than 6/60 to 3/60 or visual field less than 20 up to 10 degrees around the center of fixation and the best corrected worse eye is less than 6/60 to 3/60. For data collection and analysis, we utilized a mixed-method approach within this research. We used thematic analysis for qualitative data analysis and descriptive and inferential statistics for quantitative data analysis.

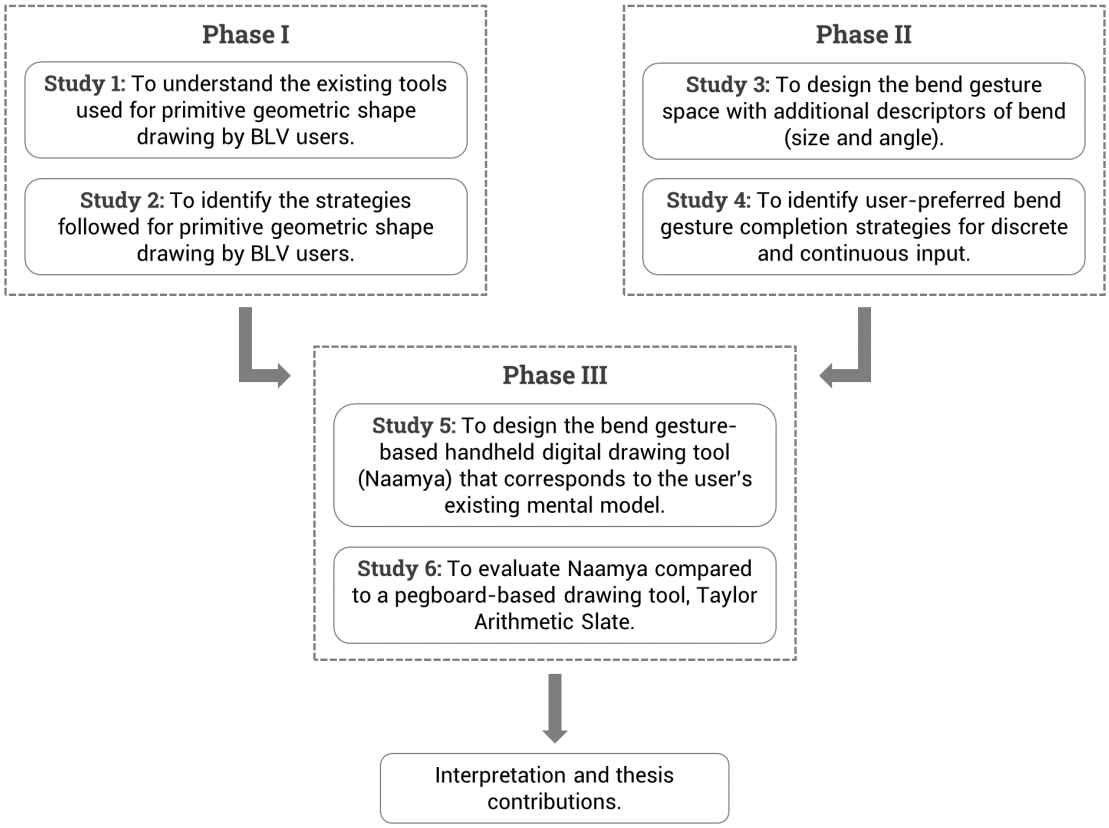


Figure 1.1: Block diagram representing the flow of this thesis work comprising three phases.

As shown in Figure 1.1, this thesis work is broadly divided into three phases comprising six studies. The detailed methodologies followed for each study are reported in the corresponding chapters. The first phase, Phase I, comprises Study 1 and Study 2. In Phase I, the first study (Study 1) aims to understand the existing tools used for primitive geometric shape drawing by BLV users. In Phase I, the second study (Study 2) aims to identify the strategies followed for primitive geometric shape drawing by BLV users. This first phase answers the first research question, RQ 1. The second phase, Phase II, comprises Study 3 and Study 4. In Phase II, the first study (Study 3) aims to design the bend gesture space with additional descriptors of bend (size and angle) considering the BLV user group's performance and preference. Study 3 answers the second research question, RQ 2. In Phase II, the second study (Study 4) aims to identify user-preferred bend gesture completion strategies for discrete and continuous input to reduce unwanted or unintended input. Study 4 answers the third research question, RQ 3. The third phase, Phase III, comprises Study 5 and Study 6. In Phase III, the first study (Study 5)

aims to design the bend gesture-based handheld digital drawing tool (Naamya) that corresponds to the user's existing mental model. Study 5 answers the fourth research question, RQ 4. In Phase III, the second study (Study 6) aims to evaluate Naamya compared to a pegboard-based drawing tool, Taylor Arithmetic Slate. Study 6 answers the fifth research question, RQ 5. Finally, we interpret the findings from all the studies and discuss the contributions of this thesis and their implications.

1.4 Contributions

The following four are the major contributions of this thesis:

1. Findings and analysis of user research on geometric drawings by students with blindness or low vision in India. These findings include the following - academic challenges and suggested reforms, limited features of current drawing tools and scope for improvement, and scope for improvement through technological intervention (presented in Section 3.1 of Chapter 3) and drawing patterns, strategies used for drawing and reading primitive geometric shapes (triangles and rectangles), errors in drawing and reading shapes, and a set of functions to design a digital drawing tool that corresponds to the user's mental model of using existing drawing tools (presented in Section 3.2 of Chapter 3).

2. A set of recommendations to design bend gesture-based interaction with basic and additional descriptors of bend gestures considering the performance and preference of users with blindness or low vision (presented in Section 4.1 of Chapter 4).

3. A set of bend gesture completion strategies that can be utilized while designing for users with blindness or low vision (presented in Section 4.2 of Chapter 4).

4. A bend gesture-based smartphone-sized flexible handheld digital tool (Naamya) for drawing primitive geometric shapes that corresponds to the user's mental model of using existing tactile pegboard-based drawing tools (presented in Section 5.1 of Chapter 5). Evidence that the bend gesture-based digital drawing tool (Naamya) and the pegboard-based drawing tool (Taylor Arithmetic Slate) are equally effective in drawing primitive geometric shapes containing straight lines (presented in Section 5.2 of Chapter 5).

1.5 Thesis Organization

The content of this thesis is laid out in the following chapters.

Chapter 1 titled **Introduction**, introduces the research context and motivation behind conducting this research in Section 1.1. This is followed by research questions reported in Section 1.2 and an overview of the research methodology reported in Section 1.3. Further, Section 1.4 presents this thesis's contributions, followed by this brief overview of the thesis's structure.

Chapter 2 titled **Review and Analysis of Existing Literature**, reports the focus areas of the conducted literature review, followed by a detailed description of each primary section covered in the reviewed literature. These sections include - challenges of people with visual impairment or blindness in using technology reported in Section 2.1, drawing tools for people with visual impairment or blindness reported in Section 2.2, and bend gesture-based interaction reported in Section 2.3. This is followed by the critical appraisal of the literature review in Section 2.4, research questions reported in Section 2.5, and the research aim and objectives reported in Section 2.6.

Chapter 3 titled **Understanding Current Use of Drawing Tools**, reports detailed user research on geometric drawing by students with blindness or low vision in Northeast India. This chapter is further divided into two major sections. The retrospective study conducted with students with blindness or low vision and their teachers is reported in Section 3.1. This is followed by Section 3.2, where we reported the direct observational study conducted with students with blindness or low vision while they were drawing primitive geometric shapes (rectangles and triangles) on a Taylor Arithmetic Slate.

Chapter 4 titled **Bend Gesture-based Interaction on Smartphone-sized Flexible Devices**, reports the investigation of bend gesture space and gesture completion strategies. We investigated the size and angle of bend gestures as two additional descriptors of bend gestures in addition to the location and direction of bend gestures. Section 4.1 reports BLV and sighted users' performance and preference for two magnitude levels of size and angle of bend on a smartphone-sized deformable prototype. Further, bend gesture completion strategies for discrete and continuous inputs are reported in Section 4.2.

Chapter 5 titled **Design and Evaluation of Naamya**, reports the final contribution of this thesis. This chapter is divided into two major sections. Section 5.1 reports the participatory

design of the bend gesture-based digital drawing tool named Naamya. In Section 5.2, we reported the comparison between the bend gesture-based drawing tool with the pegboard-based drawing tool.

Chapter 6 titled **Discussion on Contributions and Implications**, presents and discusses this thesis work's contributions and implications. This thesis work laid out four major contributions, including the design of Naamya. In this chapter, these four major contributions are discussed in detail with their research and design implications.

The final chapter of this thesis, **Chapter 7** titled **Conclusion, Limitations and Future Scopes**, provides concluding remarks on the thesis reported in Section 7.1. This is followed by the limitations of this research and the scope for future research reported in Section 7.2.

Chapter 2

Review and Analysis of Existing Literature

The previous chapter (Chapter 1) introduces the research context and motivation behind conducting this research, followed by research questions, an overview of the research methodology, the contributions of this thesis, and a brief overview of the structure of this thesis. This chapter presents and discusses the review and analysis of existing literature.

This work is informed by prior research on drawing tools for users with visual impairment or blindness along with bend gesture-based interaction with flexible handheld devices since our research aims to investigate the potential of bend gestures as the primary input modality of a digital drawing tool. Broadly this review of existing literature is an intersection of three focus areas: challenges of people with visual impairment or blindness in using technology (reported in Section 2.1), drawing tools for people with visual impairment or blindness (reported in Section 2.2), and bend gesture-based interaction (reported in Section 2.3).

2.1 Challenges of People with Visual Impairment or Blindness in Using Technology

The increasingly vision-centered world gives rise to several challenges for individuals with visual impairment or blindness. One of the biggest challenges for the visually impaired and especially people with blindness is the self-initiated physical navigation in a place to which they are not accustomed (World Access for the Blind, 2015). Moreover, the increase in the

use of graphical information in various environments in everyday life is becoming a barrier (Emiliani, Stephanidis, Lindstroem, & Jannson, 1991). For example, locating or searching for an object in a new environment, understanding info-graphics at office work, and reading, understanding, and creating alphanumeric and graphical information (Grussenmeyer & Folmer, 2016), to name a few. Similarly, the potential of technology to connect people, exchange information, and access education, employment, and entertainment is more rapidly changing and more visually demanding. An increase in visual demand excludes the visually impaired or blind from this network of technology use (World Access for the Blind, 2015). As reported by Boyd, Boyd, & Vanderheiden, 1990, in the era of the command line input, blind persons were as effective as sighted persons in using computers as they both interact with the keyboard. However, the use of a graphical user interface (GUI) has become a challenge as they demand visually rich interactions. But screen readers have made the graphical user interfaces accessible to visually impaired or blind users with a keyboard to provide input using computers. However, as a cheap alternative to computers (Leporini, Buzzi, & Buzzi, 2012), Smartphones and tablets are commonly used to increase the literacy of people (Leporini et al., 2012; Horsford, 2016). Nevertheless, the visually demanding touch interaction technique has again become a barrier to the technology use of visually impaired or blind users.

Handheld touchscreen devices such as smartphones, in particular, are becoming more common because of their direct interaction feature with the elements of a graphical user interface (GUI). It makes the interaction easier to learn and use than physical button-based interfaces by sighted users. At the same time, for the user group with visual impairment or blindness, interacting with this more visually demanding interface through direct touch is equally more difficult to learn without a sighted assistant and challenging to use without tactile buttons. Although screen readers are available, the lack of tactile buttons results in minimum spatial visualization, which leads to poor direct interaction with the intended target. Moreover, diversity in application interface layouts forces the users to continue discovering the elements on the screen whenever they switch to a new application. To interact with the touchscreen devices through audio feedback requires the user to perform a number of touch gestures (Arroba, Vallejo, Araujo, Fraga, & Moya, 2011) and to pay continuous attention to the audio feedback. Interacting with the screen reader by performing accurate touch gestures

itself is a challenge for new users of touchscreen devices (Oh et al., 2013). Moreover, frequently performing gestures on the screen creates an occlusion in collaborative work with sighted users. Text entry, which is the fundamental task of digital devices, is difficult for blind users due to the lack of a tactile keyboard and physical affordances for visualization of the virtual keyboard (Nicolau, Montague, Guerreiro, Rodrigues, & Hanson, 2015). The authentication process also raises security issues for people with visual impairment or blindness (Briotto Faustino & Girouard, 2018b). For example, user authentication on a screen reader-based system using a personal identification number and login credentials for any web or mobile application. One of the major challenges faced by users with visual impairment or blindness is access to increasingly used graphical information on digital devices. The graphical information related to static or dynamic maps, statistics, compound geometric shapes, node-link diagrams (flow diagrams, relational models, block diagrams, and molecular structures), graphs, and pictures in websites and mobile applications are commonly found in educational, commercial, and financial applications. Better accessibility of this graphical information is extremely important for the academic, personal as well as professional life of people with visual impairment or blindness. Especially for school students with visual impairment or blindness, learning, creating, editing and understanding geometric shapes two-dimensional (2D) and/or three-dimensional (3D) plays an important role in learning to handle real-world objects and interacting with other objects in the environments.

Moreover, drawing is also important for developing fine motor skills and creativity and a better understanding of spatial relationships. The use of predefined textual description enables the graphical information to be accessible to blind users through a screen reader. However, accessing the information of a particular region in a diagram, navigating, creating, editing, and sharing the information and performing collaborative work with sighted users on touchscreen devices often becomes challenging tasks for users with visual impairment or blindness (Bornschein & Weber, 2017). As smartphones are the most commonly used and carried digital devices (Kane et al., 2009) by blind users, investigating and addressing these challenges in a smartphone platform will be beneficial for visually impaired or blind user groups. Moreover, the literature on users with visual impairment or blindness using digital devices has shown that there is limited work in reading, creating, editing and understanding spatial information of 2D and 3D graphical information.

2.2 Drawing Tools for People with Visual Impairment or Blindness

To quickly communicate concepts and ideas, sighted users often take advantage of visual diagrams containing 2D and/or 3D perspective representations of objects or 3D models. Non-artistic 2D or 3D drawing on a digital tool or software may not be very challenging for a sighted person. Drawing a picture is to bring the mental model of an image from the mind to paper. For a person with blindness, the mental model of an object is generated via tactile and audio senses rather than visual perceptions, which makes the process of drawing more challenging. A visually impaired or blind person also needs to draw diagrams as a requirement of academic or professional tasks and also expresses interest in 3D drawing. Existing literature presents the challenges of drawing an object and different techniques to draw a digital image by people with visual impairment or blindness. In this section, we review the existing literature on drawing tools for people with visual impairment or blindness. This section is divided into two subsections. First, we discuss the existing research on drawing tools that employed various input devices which provide tactile and haptic feedback other than touch-based input. For instance, keyboards, haptic devices, tactile grids, and braille displays. In the second subsection, we discuss existing research to facilitate people with visual impairment or blindness to utilize touch-sensitive devices for digital drawing.

2.2.1 Digital drawing with tactile and haptic devices

T-Draw (Kurze, 1996) is one of the first tools used to study blind users' mental models of the 3D world. They tried to answer the question, "what do pictures for the blind look like". The author used a digitizer tablet, heat-sensitive swell paper and a Digitizer Pen combined with a Thermo Pen as a method of input. To draw and digitally record the diagram, the swell paper is placed on top of the tablet. Two geometric objects: polygons and lines or sequences of lines, were considered for the study. When the object is being drawn, its attributes, names and descriptions are spoken to the user. Using T-Draw, a polygon is recognized by triggering a voice command when a line ends near the beginning of another line. Only a Digitizer Pen is used to explore the drawing. When the pen approaches a line or is inside a polygon, the

respective description is provided using a Text to Speech (TTS) system. As heat-sensitive swell paper was used, drawings cannot be edited. As reported by the author, participants faced difficulties in drawing straight and parallel lines. They discussed that blind users do have a spatial mental model of real-world objects. But when they transformed a 3D model into a 2D drawing, they failed to add the spatial relationship between the surfaces as if the surfaces were drawn from a different viewpoint.

To address the problem of computer-aided drawing for the visually impaired without using special purpose external devices, Kamel & Landay, 1999 introduced the Integrated Communication 2 Draw (IC2D) system. It has a user interface that enables navigation and drawing using audio feedback. Input for navigation and point selection is done via a new recursive grid scheme based on the layout of the telephone keypad grid. The IC2D user interface provides access to nine fixed screen regions in a 3x3 grid corresponding to the numbers on the Numpad of the computer keyboard. Later the authors reported a user study conducted with five (3 blindfolded partially sighted and two totally blind) participants using a tactile graphics tablet (Kamel & Landay, 2000). They hypothesized that "drawing tools for blind users that simply adapt methods used by sighted users are not sophisticated enough to compensate for a lack of visual feedback". Participants were informed that testing their artistic talent was not the study's goal but rather the evaluation of the functionality of the drawing tool. Participants were asked to draw a set of objects and a freehand drawing as a part of the tasks. After completing all the tasks, all the participants were asked to compare what they drew with what they intended to draw either by looking (for partially blind) or using touch (for blind). Results showed that drawings were not as intended to be in the participants' minds. After analysis of the results, they reported that a successful drawing model must provide a way for relocating absolute as well as relative points, provision to evaluate the length of a line, angles between lines, and access to maintain curvature in the drawing. Later, the authors examined their previously developed grid-based drawing model IC2D (Kamel & Landay, 1999) and described how this model offers the properties of the successful drawing model. They also discussed that the familiarity of users with telephone keypads helped to improve the learnability and memorability of IC2D's grid-based metaphor. They reported that IC2D permits blind users to easily select points, relocate them later, measure equal lengths, replicate angles and properly close figures. This presents the usability

of the graphical tool (IC2D) using the grid-based drawing approach.

Later, one of the authors of this work (Kamel & Landay, 2002b), blind since the age of 23, drew a cube in IC2D, which was a recreation of the cube drawn using T-Draw (Kurze, 1996). With the help of IC2D, the user was able to evaluate the length of lines, determine and recreate angles, and close the figure properly. As in the telephone keyboard (Numpad), the placement of the keys (in the 3x3 grid) matches real-world spatial directions (left, right, up, down, and diagonals), and this grid-based technique was found to be more effective. Kamel & Landay, 2002a also tested IC2D extension to enable visually impaired users to view (via audio for the blind) and create 2D animations with 2D repeated movements. Kamel & Landay, 2002b also found that for a set of assigned tasks, visually impaired participants performed as well or better than the blindfolded sighted participants in terms of time, user confidence, and the judge's rating for tasks. For the third task, they gave participants (8 visually impaired or blind users and 8 blindfolded sighted users) a physical cube and asked them to draw it, preserving the 3D effect as much as possible. The goal of this task was to see if the grid-based interface would allow participants to visualize and draw real-world objects. The results show that a grid-based model is useful for allowing visually impaired or blind users to create graphics and identify relative and absolute positions. They also found that participants were able to visualize spatial representation of objects from the output of IC2D and preferred labelling of objects for better visualization.

T. Watanabe & Kobayashi, 2002 developed a refreshable Braille display-based drawing tool that enables users to draw and freely erase any portion of their drawings. The input for drawing an object was provided by a stylus connected to a 2-axis arm. The display also allows users to read existing digital copies through haptic feedback.

A multimodal (haptic and auditory) web-based tool has been developed by (Yu et al., 2003) to allow blind users to create and explore virtual graphs independently by using a low-cost haptic mouse and audio feedback. It was found to be significantly more effective and efficient than using only audio or haptic feedback.

Brown, Pettifer, & Stevens, 2003 developed Kekul´e, a software designed to enable visually impaired users to explore the structures of chemical molecules using speech-based feedback. A computer keyboard was used to provide input for browsing the structure in either a connection-based or hierarchical manner, and the description was presented in the

form of speech. They reported that participants found the software easy to use and able to explore molecular structures more easily. However, the system did not support the creation of a new molecular structure.

D. K. McGookin & Brewster, 2006a reported the initial work of the project named MultiVis, which allows visually impaired users to construct and browse mathematical graphs. They found that the use of PHANTOM Omni haptic devices for creating a virtual haptic environment and non-speech audio for feedback can be used to overcome the basic challenges faced by visually impaired users in drawing graphs. They also developed Sound-Bar (D. K. McGookin & Brewster, 2006b), a graph browsing system to read bar graphs. It provides an overview of the graph by means of non-speech sound while interacting with PHANTOM Omni Haptic Device.

Miller, 2006 developed Deep View, a tool to enable blind users to create and edit node-link diagrams. The system supported collaborative drawing with sighted users. However, it does not present a diagram's spatial layout. In Deep View visual diagram was provided for a sighted person, while an audio representation of the same diagram was provided to the blind users. The edit menu and/or keyboard shortcuts are used to add nodes or links as well as to edit the selected node/link.

Rassmus-Gröhn, Magnusson, & Eftring, 2007 presented the initial design of an audio-haptic drawing program. The system allows visually impaired users to create and access graphical images using the PHANTOM Omni haptic device. A user can access the diagram using audio and haptic feedback. For creating the diagrams, either a mouse or PHANTOM device could be used. The author reported that all participants were able to complete the assigned tasks using the system.

Metatla, Bryan-Kinns, & Stockman, 2008 described the design of two interaction strategies (guided and non-guided) for constructing a relational diagram in an audio-only interface. Results of a within-group study with 24 sighted participants indicated that a non-guided strategy supports faster interaction, while a guided strategy reduces browsing and exploration steps. They also suggested that interaction time in guided strategy can be reduced with the help of Spearcons (speech-based earcons) or by decreasing the content and increasing the speed of the speech feedback in a proper manner.

D. McGookin, Robertson, & Brewster, 2010 implemented Tangible User Interface (TUI)

technology to provide access to bar graphs and line graphs using a tangible grid, data sonification and physical icons (phicons). Selected physical icons were of different textures, shapes, and weights so that participants could easily distinguish them. The bottom side of each physical icon was marked with a fiducial marker that can be tracked by a 3D space camera (located below a glass surface) to sense the drawing and to trigger audio feedback. The audio feedback was spatially panned to the left or right stereo channels for better spatial visualization. All the participants were able to complete graph construction and browsing tasks using bi-manual interaction strategies.

GSK (Balik, Mealin, Stallmann, & Rodman, 2013), a Graph SKetching tool that allows blind and sighted people to easily read, create, edit, and share graphs in real-time by using interaction mechanisms such as a mouse (for sighted), keyboard (for both blind and sighted), monitor and screen reader. GSK was designed to offer the same type of experience as a blind and a sighted person feel working together on a text or word processing software. GSK supports two views of the graph, Connection View for the sighted user and Grid View for visually impaired or blind users. Grid View provides blind users with the ability to spatially lay out a graph. The second author, who is a person with blindness, tested the system and found it to be efficient for independent drawing. In order to determine how well GSK functions for other blind individuals, they carried out a user study with eight blind participants (Balik et al., 2014). As no significant difference was found between Excel and GSK for the graph navigation study, they further simplified the system based on user feedback from the previous study. According to the authors, later, a marked improvement in GSK's response time was found as compared to Excel. The second author, as a participant, reported that GSK makes it easy to remember the graph. However, no evaluation of memory was reported in this work. The second author was also able to create a real-world compound object.

Bornschein, Bornschein, & Weber, 2018 presented a drawing workstation for blind users containing a two-dimensional tactile pin-matrix display for input and real-time tactile output of drawing and feedback. They implemented four input modalities: menu-based approach, gesture recognition, stylus-based freehand drawing and capturing of object silhouettes by a 3D depth camera. A comparative study conducted with twelve blind users showed that all modalities are highly appropriate for drawing tasks. The input modalities helped to improve the quality of the drawing. They also found that direct manipulation works well for blind

users at the position of the reading hand but not far beyond the current region of interest. They reported that the system is suited for creativity tasks as well as cooperation with sighted people for sharing ideas graphically.

Memeo, Jacono, Sandini, & Brayda, 2021 proposed a mouse-shaped handheld actuator with three degrees of freedom (elevation, roll, and pitch) to enable users with visual impairment or blindness to learn three-dimensional digital information via tactile feedback provided on one finger. Local tactile height and inclination cues are provided by the actuator to enable users to explore the virtual objects. The authors evaluated the efficiency of the system by conducting a virtual and real object-matching task with blind and blindfolded sighted participants. Findings indicate that both elevation and inclination cues were sufficient, and the combined cues provided the best results.

Fernando & Ohene-Djan, 2021 developed SETUP09, a graphics creation system where users can create, manipulate, and navigate graphics content by providing commands using a keyboard. The system provides voice feedback to confirm user input. This system offers matrix-style movement with nine cardinal/compass directions considering it to be an intuitive exploration style. The authors evaluated the proposed system compared with an analogue raised-line drawing tool with early and late blind individuals. The authors reported that the compass-based graphics creation technique of SETUP09 allows for higher accuracy in completing drawing tasks with reduced effort. The author also reported that analogue drawing time was shorter than digital drawing time, although the difference was not statistically significant. They also observed that late blind participants performed better on the raised-line drawing tool, while for the keyboard-based digital drawing system, both late and early blind participants performed similarly well. According to the authors, the grid-based navigation technique with nine cardinal directions was found to be reliable and effective, and it facilitates a better drawing tool than the analogue raised-line drawing tool.

2.2.2 Digital drawing with touch-sensitive devices

Audiograf (Kennel, 1996) is one of the initial works that used touch panels combined with audio feedback to enable visually impaired or blind users to read diagrams. The diagram is displayed on the touch panel. Whenever a segment of the diagram is touched with the finger, corresponding audio feedback is conveyed to the user. This way, the whole diagram can be

explored in an audio-tactile manner. They followed one-to-one mapping, that is, a particular point on the screen represents particular information instead of providing a full description of the diagram. This navigation enables the user to understand the spatial layout of the graph. Each diagram consists of basic types of graphic elements, and their attributes give the description of the graphic elements. Users were able to read simple diagrams within a short period of time.

Blenkhorn & Evans, 1998 presented a novel approach to allow blind users to interact with computer-generated graphical information. It allows blind users to read, create and edit a schematic diagram (data flow diagram). The system consists of a touchscreen tablet covered by a tactile overlay with hapticons (haptic icons) and a speech synthesizer for audio feedback. They evaluated the use of hapticons on tactile layout, and the results show that users prefer hapticons of medium size with symmetry and represented with a continuous shape for easy recognition. However, the ease of navigation using the layout was found to be below average.

PLUMB (Calder et al., 2006) was developed to help blind students comprehend graphs and data structures by means of speech and musical tone feedback. They used a tablet PC with a stylus. The graph was presented in the form of speech, and the stylus (pen) was used to navigate from vertex to vertex along the edges. Information about the movement of the stylus along the edge was conveyed by a continuous musical tone with a vibrato effect that increased in intensity at the end of the edge, indicating that a node had been reached. To keep the user on the edge while navigating, the tone's loudness decreases as the user moves farther from the central axis of the edge. When a vertex was reached, a sound was played, and its name and a brief description were spoken out. PLUMB's exploration of the graph also provides a spatial representation of the graph to users with visual impairment or blindness. When no element was in focus, general information about the graph was provided instead. According to the authors, the later version of PLUMB also incorporated keyboard navigation using arrow keys and shortcuts.

Grussenmeyer & Folmer, 2016 created an initial prototype of a drawing tool, AudioDraw, to make geometric shapes accessible and to discover the potential of people with visual impairment or blindness using touchscreens for drawing. They revised the initial prototype based on user feedback and conducted a design probe study with eight visually impaired participants. They used a touchscreen tablet to implement the system using predefined shapes

with fixed sizes to make the application more general and usable. Text to Speech (TTS) engine was used for audio feedback during drawing. The authors evaluated the ease of using five techniques implemented in the system - positioning technique, direction facing technique, compass directions (with respect to the center of the screen), inches information, and tactile feeling (audio-tactile). They reported that the participants were able to drag and drop shapes on the touchscreen, and the techniques were easy to use, especially the positioning technique and the compass directions. In addition, they reported that participants were enthusiastic about the ability to create their own diagrams using a touchscreen device.

Z. Zhang & Wobbrock, 2022 proposed A11yBoard, an interactive system that makes reading and creating content on digital artboards accessible to users with blindness or low vision. This interactive multimodal system combines a web-based application with a mobile touchscreen that mirrors the content from a computer to enable touch-based spatial exploration of the artboard. Users can provide input to the system using a keyboard with a custom search-driven command line interface, and non-speech audio feedback is provided for output. According to the authors, this system will allow users with blindness or low vision to both read and create digital content.

2.3 Bend Gesture-based Interaction

In this section, we present and discuss prior research on deformation gesture-based interaction, bend gestures to interact with deformable devices, the potential of deformation gestures over touch-based interactions, descriptors of bend gestures, and bend gestures for people with visual impairment or blindness.

2.3.1 Deformation gesture-based interaction

Today's mobile devices are mostly built around touch-input interaction. It has dominated keypad-based devices by providing a more easy-to-use interaction modality with a larger input and output real estate. Still, research is going on to provide new interaction modalities to enhance and complement the existing input methods. Physical manipulation (Harrison et al., 1998) or deformation of the handheld device (Schwesig et al., 2003) as a means to provide input is one of the many attempts that have been made to create new interaction

modalities. The rapid advances in flexible electronics and displays confirm the potential of deformation gestures for future flexible display devices (W. S. Wong, Chabinyc, Ng, & Salleo, 2009; Nathan et al., 2012; Boem & Troiano, 2019; Zhou et al., 2021; Wu et al., 2021). These thin and lightweight displays provide the physical affordances of flexible or deformable paper (Wightman et al., 2011). This scope for deforming the display can be used as an explicit input method which introduces deformation gestures as an alternate input interaction modality (Schwesig et al., 2003, 2004). The mode of providing input to a deformable user interface is through physical manipulation of the form factor of the deformable device (Harrison et al., 1998; Schwesig et al., 2003, 2004). Users can provide distinct inputs through different types of deformations such as bending, twisting, folding, rolling, crumpling, tearing, and stretching the device (Kildal et al., 2012; S. S. Lee et al., 2010). Such device deformations during interaction can be monitored using embedded sensors and mapped to trigger specific functions or actions. However, bending the device to provide deformation gesture-based input (bend gestures) is commonly explored and investigated in the literature for both one-handed (Girouard et al., 2015; Ernst et al., 2017; Borah & Sorathia, 2019b) and bi-manual (Schwesig et al., 2003; Lahey et al., 2011; Kildal et al., 2012; Warren et al., 2013; Daliri & Girouard, 2016; Faustino et al., 2020) interactions.

2.3.2 Bend gestures to interact with deformable devices

Bend gestures on a deformable handheld digital device offer a novel input interaction modality. According to literature, bend gesture-based interaction is comparable to touch (Burstyn, Banerjee, & Vertegaal, 2013). Bend gestures can address the challenges of touch input, such as reachability during one-handed interaction (Girouard et al., 2015) and spurious input while holding the device (Wightman et al., 2011). According to Ahmaniemi et al., 2014, bend gestures are optimal for providing quick continuous bipolar input with a better spatial directional similarity to represent continuous metaphors. They also reported that, unlike multi-touch pinch gestures, deformation gestures to provide continuous input do not occlude the screen with fingers. Although the touch user interface allows direct user interaction, it highly demands visual attention. In contrast, deformation-based gestures offer the potential of eyes-free interaction (Cheung et al., 2017). The most significant advantage of bend gestures is the innate tactile and kinesthetic feedback (Wightman et al., 2011) that is

missing in touch-based input (Holman et al., 2005). Bending the device requires the user to apply a certain amount of force on the flexible device in a particular direction (Kildal, 2012). This application of force allows users to perceive the tactile and kinesthetic feedback during bend gesture-based interaction. This feedback provides the sense that it resembles physically working with digital documents (J. I. Watanabe, Mochizuki, & Horry, 2008). As a result, this tangible interaction enables both sighted and visually impaired users to interact with digital devices using bend gestures. Ernst et al., 2017 reported that the bend gesture-based interaction could be a promising complement to the existing mobile interaction, especially in terms of improving the accessibility of mobile input interaction. They also reported that users with visual impairment or blindness found bend gestures easy to learn and perform.

2.3.3 Potential of deformation gestures over touch-based interaction

A common interaction technique of most handheld devices is touch-based input. It allows users to interact directly with the device's graphical user interface. However, visual occlusion due to interacting finger(s) plays the role of major drawback in touch (Karlson & Bederson, 2007; Roudaut, Huot, & Lecolinet, 2008; Boring et al., 2012) and multi-touch devices (Benko, Wilson, & Baudisch, 2006; Vogel, Cudmore, Casiez, Balakrishnan, & Keliher, 2009). Moreover, for large screen handheld devices, one-handed interaction presents the challenge of unreachable target areas (S. Kim, Yu, & Lee, 2012; Girouard et al., 2015; Sorathia, Singh, & Chhabra, 2017), difficulty in multi-touch interaction (Boring et al., 2012) and frequent re-gripping during interaction (Girouard et al., 2015). Unlike touch input, occlusion and reachability are not challenges of deformation-based interactions (Girouard et al., 2015). It enables eyes-free interaction (Cheung et al., 2017) that is independent of the spatial distribution of GUI elements, offers robustness to spurious interaction when handling the device (Wightman et al., 2011), and provides an optimal mean for quick continuous bipolar input (Ahmaniemi et al., 2014). Performing deformation gestures offers a better spatial directionality to represent continuous metaphors (Ahmaniemi et al., 2014). Ahmaniemi et al., 2014 also reported that, unlike multi-touch pinch gestures, deformation gestures to perform continuous actions do not occlude the screen with fingers. While performing a deformation gesture, both hands can remain gripping the device throughout the

interaction (Kildal & Boberg, 2013; Burstyn et al., 2013) to minimize the re-gripping issue of the touchscreen-based devices. The most significant advantage of deformation gestures is the capability to provide tactile as well as kinesthetic feedback (Wightman et al., 2011) that is missing in touch-based interaction (Holman et al., 2005). This tangibility provides the "good feeling" (J. I. Watanabe et al., 2008) of a real book page-turning sense that resembles physically working with digital documents (J. I. Watanabe et al., 2008).

2.3.4 Descriptors of bend gestures

Bend gestures are naturally associated with two descriptors, which are location and direction of bend (S. S. Lee et al., 2010; Lahey et al., 2011; Warren et al., 2013). Gummi is the first deformable handheld computing device prototype with a user interface where the user provides input through bend gestures (Schwesig et al., 2003, 2004). Gummi reported a threshold-based gesture completion strategy where it interprets deformation as continuous analogue input until the deformation reaches a certain threshold to recognize it as a discrete gesture. The bend gestures used in Gummi can be described in terms of the location and direction of bend gestures. For instance, while holding the device in landscape mode, the prototype's center (on the horizontal axis) was the target location that could be bent either towards the upward or downward direction. A spatial similarity was maintained between the location of the selected item around the center of the screen and the location of the bend gesture. They reported that participants found this bend gesture-based interaction on Gummi to be feasible, effective, and enjoyable (Schwesig et al., 2004). Existing literature (S. S. Lee et al., 2010; Wightman et al., 2011; Lahey et al., 2011; Kildal, 2012; Kildal & Wilson, 2012; Burstyn et al., 2013; Ahmaniemi et al., 2014; Girouard et al., 2015; Daliri & Girouard, 2016; Strohmeier et al., 2016; Maqsood et al., 2016; Ernst et al., 2017; Lo & Girouard, 2017; Faustino et al., 2020) has explored and investigated bending the deformable device at different locations and two directions as basic descriptors of bend gestures to provide input. These locations commonly include corners (S. S. Lee et al., 2010; Lahey et al., 2011; Maqsood et al., 2016; Daliri & Girouard, 2016; Ernst et al., 2017; Lo & Girouard, 2017; Faustino et al., 2020) and sides (S. S. Lee et al., 2010; Lahey et al., 2011; Dibeklioğlu et al., 2011; Maqsood et al., 2016; Lo & Girouard, 2017) of the handheld flexible devices. Researchers have also studied folding (Gallant, Seniuk, & Vertegaal, 2008; S. S. Lee et al.,

2010; Maqsood et al., 2016), twisting (Kildal, 2012) and stretching (S. S. Lee et al., 2010) the device in addition to bending using the two basic descriptors. Lee et al. (S. S. Lee et al., 2010) studied user-defined bend gestures with three materials (plastic sheet, paper, and elastic cloth) of different physical properties. They found that the level of consensus among the users regarding intuitiveness and preferences for proposed gestures enhanced with the increased flexibility of the material. As this work studied user-defined gestures, they reported a diverse set of gestures performed at different locations and directions with different types of deformations.

Warren et al., 2013 proposed a classification scheme for deformation-based gestures. They reported seven potential descriptors of bend gestures that will allow users to perform a large set of gestures and out of those seven descriptors, four descriptors (location, direction, size, and angle) were investigated in detail. They studied user performance for 36 unique gestures with three locations, two directions, and three magnitude levels of each size (size of the bent area) and angle of bend. They conducted this study with 13 sighted participants on a letter-sized deformable prototype. They found strong agreement among the participants for preferred locations and directions. They reported that the participants preferred two levels of magnitude for both size and angle. They (Warren et al., 2013) also recommended using either size or angle for novice users to avoid confusion. Although this research studied the user preference and performance for four descriptors of bend gestures, it includes the gesture locations only from the right side of the letter-sized flexible prototype and the study was conducted with only sighted participants. However, a very limited number of research works explored and investigated bend gestures with additional descriptors other than location and direction of bend. Daliri & Girouard, 2016 reported the use of two magnitude levels of angles that included half and full angles of a bend gesture. They used the half activation of the bend gesture to trigger feedback indicating that the user needs to increase the bend to activate the gesture completely. Maqsood et al., 2016 also recommended the use of bend gestures with different angles of bend for their proposed bend gesture-based user authentication system. Users' own strategies based on different scenarios often make the gestures distinct, easy to learn and remember (Ashbrook & Starner, 2010; C. Zhang, Jiang, & Tian, 2016). Similarly, to expand the gesture space using additional descriptors of bend gestures, understanding user performance in distinguishing the descriptors and user strategies involved in differentiating multiple magnitude levels of the same

descriptor are also important.

2.3.5 Bend gestures for people with visual impairment or blindness

Ernst & Girouard, 2016a have conducted a comparative study between seven deformation and touch gestures with simulated blind participants. This study is one of the initial works that explored the potential opportunities of bend gestures on a deformable smartphone-sized prototype for users with blindness. However, the selection of bend gestures was based on prior research conducted with sighted participants (Girouard et al., 2015) in contrast to the selected touch gestures of the screen reader of iOS, VoiceOver. They found no significant difference between the completion times of touch and bend gestures. The majority of the participants found bend gestures to be more comfortable to use than touch gestures. Researchers have also studied the use of haptic stimuli as an affordance to assist in learning bend gesture location and direction (Ernst & Girouard, 2016b). They found that the use of a single motor for a short duration resulted in a significant increase in accuracy while mapping tactile icons to a bend location and direction. Later Ernst et al., 2017 investigated the learnability and usability of the seven bend gestures to complement the existing touch-based interaction with VoiceOver. They conducted this study with a deformable prototype (typhlex) that enables haptic affordances through grooves on the device. They reported that the grooves improve the identification of locations and the ease of bending the device, and users were able to distinguish the bend gestures clearly. They found that bend gestures are easy to learn and perform and have the potential to complement the existing mobile touch interaction to offer accessible mobile interaction. Researchers have also proposed a bend gesture-based novel user authentication method (Maqsood et al., 2016). BendyPass (Briotto Faustino & Girouard, 2018a) is a handheld deformable prototype where different sequences of bend gestures are used as a password. The authors reported that this tactile input method is used for user authentication to protect personal information entered by users with visual impairment. Later, Faustino et al., 2020 investigated bend and PIN-based authentication with visually impaired or blind users. They found that as a tactile authentication method, a bend password has the potential to offer better learnability and memorability for people with visual impairment. Considering bend gestures' innate tactile and kinesthetic feedback, users with visual impairment or blindness are one of the major user groups that can take advantage of

bend gesture-based interaction. However, to the best of our knowledge, there is no research on digital drawing tools for this user group that utilises bend gesture-based interaction.

2.4 Critical Appraisal of Literature Review

The review of the existing literature on digital drawing with tactile and haptic devices by users with visual impairment or blindness (reported in Subsection 2.2.1) indicates that the use of predefined grids on the keyboard, haptic devices (PHANTOM and haptic mouse), tactile grids, and braille display offers accessible drawing environments. It further demonstrates that tactile and haptic feedback during digital drawing improves the drawings' comprehension and spatial perceptions. However, integrating these interaction techniques for handheld devices such as smartphones and tablet computers raises portability issues as they demand a set of peripheral accessories. In the meantime, this reveals the positive impact of tactile and haptic features of interaction on user performance and experience in performing reading and drawing tasks.

The review of the existing literature on digital drawing with touch-sensitive devices by users with visual impairment or blindness (reported in Subsection 2.2.2) indicates that touch-sensitive devices allow effective exploration of diagrams on the screen with better spatial perception. However, this exploration of diagrams through direct touch on a smooth touch-sensitive surface requires additional feedback, such as vibrotactile or audio-tactile feedback. This additional feedback enables users to perceive the presence of a drawing displayed on the screen to resemble active exploration by touching. However, due to the lack of tactile feedback, this use of touchscreen devices does not provide any assistance to enable users to follow a desired (straight or curved) path. Additional feedback needs to be provided to enable users to follow a desired path without deviation. This need for conveying several pieces of information indicates that the user needs to perceive and interpret this information from the provided feedback itself to explore the diagram and follow a path correctly without deviating from it. In addition to reading a diagram, this lack of tactile feedback again creates similar difficulties during drawing. Such touchscreen-based exploration is also limited by the size of the touch-sensitive device or demands frequent content shifting, which may create further difficulties during drawing on smaller handheld touch-sensitive devices such as smartphones.

The review of the existing literature on deformation gesture-based interaction (reported in Subsection 2.3.1) and bend gestures to interact with deformable devices (reported in Subsection 2.3.2) indicates that bend gestures are majorly investigated in the literature and found them easy and effective as an input modality. Users can provide a large set of inputs by bending the device at different locations and directions along with multiple levels of size, angle, and speed of bend. In addition, the review of the existing literature on the potential of deformation gestures over touch-based interaction (reported in Subsection 2.3.3) reveals that performing bend gestures on a flexible device is associated with inherent tactile and kinaesthetic feedback, which is further associated with a wide range of spatial directional cues. These tactile and kinaesthetic properties are missing in touch-based interaction on a smooth touch-sensitive surface. Existing literature on bend gestures for people with visual impairment or blindness (reported in Subsection 2.3.5) reveals that bend gestures are found to be easy to learn and perform by users with visual impairment or blindness. Considering bend gestures' innate tactile and kinesthetic feedback, users with visual impairment or blindness are one of the major user groups that can take advantage of bend gesture-based interaction. However, there are limited explorations of using bend gestures on smartphone-sized handheld devices focusing on the performance and preference of this user group.

Moreover, with the advantages of bend gesture-based input, it has the potential to be used as the primary input modality of any digital application that can take advantage of the innate tactile and kinaesthetic feedback of bend gestures and also requires the execution of functions associated with spatial directions. One such application is drawing by users with blindness or low vision, which can take advantage of the inherent tactile and kinaesthetic feedback of bend gestures and has functions associated with spatial directions (such as navigation) to accomplish drawing tasks. However, to the best of our knowledge, no prior work proposed and investigated a bend gesture-based digital drawing tool for users with blindness or low vision despite having adequate advantages of bend gestures, such as inherent tactile and kinesthetic feedback and association with spatial directions.

Such application of bend gestures that requires mapping of bend gestures to several functionalities needs a larger gesture space. In this context, gesture-completion strategies also offer the opportunity to utilize the same bend gesture for multiple functions. Moreover, the review of the existing literature on descriptors of bend gestures (reported in Subsection

2.3.4) indicates that apart from the location and direction, the other potential descriptors of bend gestures, such as size, angle, and speed have not been explored considering the users with visual impairment or blindness. As the existing literature has provided us with a rich set of descriptors of bend gestures to design usable and accessible bend gesture-based interaction for flexible handheld devices, it is crucial to understand the user performance and preferences of different user groups. In this context, investigating user performance and preference of both BLV and sighted users could further allow researchers and designers to propose more inclusive interaction opportunities. Moreover, there are limited investigations on bend gesture completion strategies in the literature, which also have the potential to reduce spurious input during bend gesture-based interaction.

2.5 Research Questions

With the insights from the review of the existing literature mentioned above, we formulated the following research questions.

RQ 1: What existing tools and strategies are followed by blind and low vision (BLV) users to draw primitive geometric shapes?

RQ 2: How should the bend gesture space be designed using additional descriptors of bend (size and angle) considering the BLV user group's performance and preference?

RQ 3: What are the preferred bend gesture completion strategies of the BLV user group to provide discrete and continuous input to reduce unwanted or unintended input?

RQ 4: How can the bend gestures be used to design a geometric shape drawing tool that corresponds to the user's existing mental model?

RQ 5: Does a bend gesture-based geometric shape drawing tool enable BLV users to draw primitive geometric shapes effectively compared to the existing drawing tool?

2.6 Research Aim and Objectives

2.6.1 Research aim

This research aims to investigate the potential of bend gestures as the primary input modality of a digital drawing tool for users with blindness or low vision. In order to accomplish this goal

by using a human-centered design approach, this research seeks to plan and execute a series of user studies involving students with blindness or low vision and their teachers. The aim of this research can be achieved through the following objectives.

2.6.2 Research objectives

1. To conduct detailed user research on drawing by students with blindness or low vision in India to gain an in-depth understanding of the use of existing drawing tools and to investigate their convention of creating and reading geometric shapes using these tools.
2. To investigate the performance and preference of users with blindness or low vision and sighted users for bend gesture-based interaction considering basic and additional descriptors of bend gestures to design the gesture space.
3. To identify user-preferred bend gesture completion strategies for users with blindness or low vision and sighted users.
4. To design a bend gesture-based smartphone-sized handheld digital tool through a participatory approach for geometric shape drawing that corresponds to the user's mental model of using existing drawing tools.
5. To compare the effectiveness of the bend gesture-based digital drawing tool with the existing drawing tool.

2.7 Summary

This chapter presented and discussed the review and analysis of existing literature. This chapter also reported the research questions formulated for this thesis work, followed by the aim and objectives of this research work. In the next chapter (Chapter 3), we reported the two studies of Phase I (Study 1 and Study 2). The first study reported in the next chapter (Study 1 reported in Section 3.1) details the retrospective study conducted with students and teachers with blindness or low vision regarding mathematical diagrams. The second study reported in the next chapter (Study 2 reported in Section 3.2) details the exploration of the existing geometric drawing tool used in schools in the Indian context and the strategies followed for

reading compound geometric shapes and drawing primitive geometric shapes (rectangles and triangles) to understand the user's mental model of using existing tools.

Chapter 3

Understanding Current Use of Drawing Tools

The previous chapter (Chapter 2) presented and discussed the review and analysis of existing literature on challenges of people with visual impairment or blindness in using technology, drawing tools for people with visual impairment or blindness, and bend gesture-based interaction. This chapter reports the two studies of Phase I (Study 1 and Study 2). The findings of these two studies of the first phase answer the first research question (RQ 1 reported in Section 1.2). The first study reported in this chapter (Study 1) details the retrospective study conducted with students and teachers with blindness or low vision regarding mathematical diagrams. The second study reported in this chapter (Study 2) details the exploration of the existing geometric drawing tool used in schools in the Indian context and the strategies followed for reading compound geometric shapes and drawing primitive geometric shapes (rectangles and triangles).

3.1 Study on Using Existing Tools for Learning Mathematical Diagrams

This work presents an interview-based retrospective study conducted with students and teachers with blindness or low vision regarding mathematical diagrams. It aims to understand the experience of students and teachers in learning and creating mathematical diagrams and the need and scope for improvement through technological interventions in the Indian

context. We conducted semi-structured interviews with ten students and four teachers with blindness or low vision and analyzed the collected data using thematic analysis. We found that students have little interest in learning and practising mathematical diagrams on analogue tools due to these tools' limited features. In addition, time-consuming mathematical drawings as a part of the academic assessment process and less awareness of their future use contribute to this reduced interest. We believe using a collaborative learning process through digital tools with tactile feedback can facilitate easy and quick understanding with a more competitive and enjoyable environment to learn mathematical diagrams. The findings of this study partially contributed to answering the first research question, "RQ 1: What existing tools and strategies are followed by blind and low vision (BLV) users to draw primitive geometric shapes?" (RQ 1 reported in Section 1.2).

3.1.1 Methodology

This study aims to understand the experience of students and teachers in learning and creating mathematical diagrams. In this scenario, the qualitative interview-based study was the natural choice of instrument as we wanted to capture their long-term experience.

3.1.1.1 Participants

We communicated with four schools belonging to two different states (Assam and West Bengal) of the North Eastern Region of India and sought prior permission from the school authority to conduct this study with the students and teachers abiding by the ethics of conducting research on human subjects. Ten students (7 male and 3 female) with visual impairment (*Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018) 100% (except 2 participants with 80%) between the ages of 18-22 years (Mean = 20.2, SD = 1.69), participated in the study. Five students were congenitally blind and the rest were late blind (impairment since 6 years old or more according to Gougoux et al., 2004). All the students have learned geometric drawing using one or more tactile drawing tools shown in Figure 3.1. Four teachers (3 male and 1 female) with visual impairment (*Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018) 100% between the ages of 35-63 years (Mean = 46.5, SD = 12.23), participated in the study. All the teachers have more than five years of experience teaching geometric drawing to students with visual impairment.

Demographic information of the participants is presented in Table 3.1. Equal numbers of schools, students, and teachers participated from each state.

Table 3.1: Demographic information of BLV participants from student (S1-S10) and teacher (T1-T4) groups.

Participant	User Group	Age	Gender	Visual impairment (%)	Impairment since
P1	Student	18	M	100	6 years old
P2	Student	19	F	100	Birth
P3	Student	20	M	100	19 years old
P4	Student	18	M	100	9 years old
P5	Student	22	M	100	Birth
P6	Student	22	M	100	Birth
P7	Student	20	M	80	11 years old
P8	Student	22	F	100	10 years old
P9	Student	19	F	80	Birth
P10	Student	22	M	100	Birth
T1	Teacher	35	M	100	Birth
T2	Teacher	40	F	100	Birth
T3	Teacher	48	M	100	Birth
T4	Teacher	63	M	100	Birth

3.1.1.2 Procedure

We conducted semi-structured interviews with each student and teacher individually, where each session was audio recorded with the prior consent of the participants. This study aims to understand the experiences in the form of challenges, needs and desires of students and teachers in learning and creating mathematical diagrams and the need and scope for improvement through technological interventions. For the student group, we asked about their experience in learning geometric drawing both in the classroom and at home, their motivation behind continuing or dropping these practices, difficulties in learning, any helpful

way of learning, and if possible, give reason to support their answers. For the teacher group, we asked them to share their experience of teaching mathematical diagrams in the classroom and their opinions regarding the need to teach them (commonly geometric drawings) to students with blindness or low vision. We asked the participants to explain their answers with examples if necessary. Later we transcribed the participants' verbal feedback by dividing them into smaller chunks of meaningful sentences.

3.1.2 Findings and discussion

We analyzed the two participant groups' verbal protocols using a thematic analysis. Two moderators coded the transcribed verbal protocols of the participants. Three high-level themes emerged at the end of the thematic analysis. These high-level themes are presented and discussed below:

3.1.2.1 Academic challenges and suggested reforms

3.1.2.1.1 Time-consuming mathematical drawings as a part of the academic assessment process:

According to the student group, sums that require drawing complex diagrams are usually more time-consuming and do not offer enough confidence to complete them correctly. In contrast, alternative subjective questions are a safer option to attempt in the examination. This result-oriented preparation has further inspired them to pay less attention to learning mathematical drawings. One student mentioned, "I like drawing shapes on pegboard, but to score better marks in the examination, I always attempt other descriptive questions than drawing". Although they often use pegboards, they rarely practice geometric drawings or explore other drawing concepts such as rotation, translation, and symmetry. According to both participant groups, learning and practising mathematical drawings should be included in the curriculum very thoughtfully so that students can not or do not need to avoid this section. At the same time, the academic assessment process should majorly focus on the effectiveness of drawing rather than efficiency.

3.1.2.1.2 Less awareness of potential use in the future:

According to the teacher group, learning mathematical diagrams and practising basic

geometric drawings should be a crucial component of the curriculum. Referring to their personal experience, learning these concepts along with reading and creating graphs gave them greater confidence in continuing their higher education with subjects requiring mathematical knowledge. They also mentioned that avoiding these mathematical concepts could adversely affect different aspects of later life, such as difficulties during involvement in spatial information-heavy tasks or discussions, collaborative work with sighted users in workplaces, and learning to navigate in a new or unknown place using verbal feedback. One teacher mentioned, "I usually read science magazines where I find fundamental mathematical terms difficult to understand". Another teacher mentioned, "No one alerted me that learning mathematics could help me in my higher education. Now I tell my students to take mathematics seriously". One student mentioned, "I wanted to study science after matriculation, but now I learned that better mathematical knowledge is required to study science. Since none of my seniors went to science stream, we never cared to study mathematics in detail". This also indicates a lack of awareness (Taraporevala, 2016) and, eventually, a lack of motivation to learn mathematics (Dey et al., 2019). According to both participant groups, the digital teaching aid by itself should offer a platform to connect to an online community that presents scenarios of the potential use and need of these concepts in post-school life.

3.1.2.2 Limited features of current drawing tools and scope for improvement

According to the student group, they often use tracing wheels, ball pens, compass, and embossed dotted 2D (two-dimensional) shapes (Figure 3.1a) to create raised-line drawings on paper or thin plastic sheets by applying pressure. They prefer to use pegboard-based drawing tools (Figure 3.1d, 3.1e, and 3.1f) for drawing purposes because of their tactile feedback during drawing and ease of modification. Instead of using dedicated tools (Figure 3.1a, 3.1b, 3.1c, and 3.1d) to learn and practice geometric shapes, they utilize commonly used pegboards such as the Taylor Arithmetic Slate (Figure 3.1f) to practice primitive geometric shapes such as quadrilaterals and triangles. Although the participants have no prior experience using digital tools for drawing, they expect ease of modification and saving the drawings for future reference on the same tool. One student mentioned, "I wish to have a pegboard controlled by my smartphone that can talk to me while I am drawing and can remember and reproduce all

the drawings that I have made in the past". Another student mentioned, "I want to connect my smartphone with a digital pegboard where I can draw using my smartphone and later I can read the diagrams on the tactile pegboard". According to both participant groups, pegboards are easy tools to draw and replicate simple diagrams, but they are not suitable for complex diagrams considering limited physical drawing space and no option for permanently saving, reusing, and evaluating the diagrams. Similar challenges were also reported in the literature (Bornschein & Weber, 2017; Grussenmeyer & Folmer, 2017).

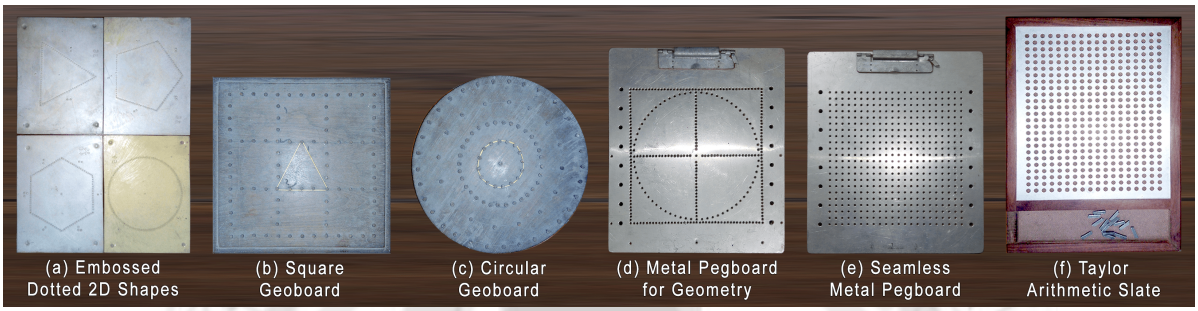


Figure 3.1: Tactile tools used by the participants for mathematical drawing.

One teacher mentioned, "It would have been easier to guide the students if we can remotely access their drawings and particularly the entire process of drawing to identify their weak and strong points". We also observed that the students usually practice right-angled triangles since the pegboard-based drawing tools do not provide enough freedom to produce different angles. Similarly, the quadrilaterals that are commonly practised are squares and rectangles. This indicates the opportunity for digital tools that offer the advantages of drawing shapes with various angles with features to modify, save, reuse, share, and evaluate the diagrams later at any point in time.

3.1.2.3 Scope for improvement through technological intervention

3.1.2.3.1 Use of digital tools with tactile feedback:

According to both participant groups, tactile feedback is crucial in any digital drawing tool, which aligns with literature (Bornschein & Weber, 2017). Along with audio and vibrotactile feedback during the interaction, the participants preferred to use a tool that enables them to perceive active touch during the interaction. According to them, the tactile feedback during active touch (Simões-Franklin, Whitaker, & Newell, 2011) offers them higher confidence

during the interaction. One participant from the teacher group has experience of using a refreshable braille display. According to him, the cost of the product could be a major barrier to using this tool, which was also reported in literature (Senjam, Foster, & Bascaran, 2021). However, he mentioned that a similar refreshable braille display with multiple rows and columns could be helpful in learning mathematical diagrams. The use of such refreshable braille display for drawing was also investigated in the literature (Bornschein et al., 2018). According to the student group, the tools for learning and practising mathematical diagrams must offer the concepts in a progressive manner where they have the freedom to learn from scratch. They also preferred these learning tools to be used as an accessory or a built-in software or hardware component of their commonly used digital device, that is, smartphones (Kane et al., 2009) due to their familiarity and easy access. This also indicates that interfaces and interaction techniques inspired by their commonly used devices may also allow them to easily adapt to new digital tools. Students also expressed their desire to experience 3D virtual objects with audio and tactile feedback. Investigation of such 3D experience was also reported in the literature (White, Fitzpatrick, & McAllister, 2008; Memeo et al., 2021; Borah, Panigrahi, & Sorathia, 2020).

3.1.2.3.2 Positive effect of the collaborative learning process:

The collaborative learning process positively impacts by enhancing the ease of understanding, expediting task completion, creating a competitive and enjoyable learning experience, and improving performance, particularly when collaborating with late blind participants. According to the student group, they prefer to discuss among themselves and often take help from each other during the tactile drawing process on pegboards. However, it is difficult to accommodate more than two users from one side of the pegboard, and working from opposite sides increases the possibility of confusion. Although the majority of them had no experience working together with sighted students, they often take help from their sighted teachers and family members when they face major difficulties during practice. Similar assistance was also observed in the literature (Sahasrabudhe & Palvia, 2013; Zebehazy & Wilton, 2014).

The majority of the participants mentioned that the collaborative learning process is helpful concerning ease of understanding and task completion time. This collaborative

learning process will be successful if the sighted collaborator understands how they work. Regarding this, one teacher mentioned, “My sighted sister helped me a lot while I was learning the geometric shapes at school, but one can not expect the same help from a sighted person who is assisting for the first time. Both the sighted and visually impaired person must know and understand to collaborate with each other”.

The students also mentioned that collaboration with other individuals with blindness or low vision, especially those who are late blind, can be very helpful if they have learned those drawings before the onset of blindness. Better performance of late blind participants during tactile drawing was also reported in the literature (Fernando & Ohene-Djan, 2021). One student referred to his late blind friend and mentioned, “He had seen these geometric shapes before he lost his vision and now he can read these shapes by touching with fingers and palms. So when he explains these shapes to me, he can provide more details that make it easy to understand”.

According to the teacher group, collaborative learning is helpful and makes the process competitive and enjoyable if more than one person can work together on the same problem using the same or different devices. The advantages of collaborative learning were also reported in the literature (Rassmus-Gröhn et al., 2007). One teacher mentioned, “Students often try to help each other while learning difficult concepts. However, in the case of drawing, multiple students working on the same tactile pegboard create difficulty and confusion among the students. Even if they draw on separate boards, in the end, it is difficult to compare the drawings with one another”. This indicates the need for a digital device where students can work on the devices individually, and the software of the tool offers the collaborative feature to connect with peers and work on the same drawing in a parallel manner or to compare their drawings with each other through both automated and manual process.

3.2 Study on Strategies Used for Primitive Geometric Shape Drawing on Pegboard

In the previous retrospective study (reported in Section 3.1), we identified that students have little interest in learning and practising mathematical diagrams on analogue tools due to these tools' limitations and limited features. We also identified that there is a scope for improvement through technological interventions that correspond to the user's mental model of using existing drawing tools. The development of a human-centered design solution to address these issues and match the user's existing tactile drawing techniques requires a detailed understanding of the current process. Intending to understand the method of reading compound shapes and drawing primitive shapes (triangle and rectangle) to help design digital drawing tools, we conducted this direct observational study. In this study, we observed tactile reading and drawing tasks followed by semi-structured interviews with 10 blind and low vision (BLV) students. We analyzed the data through thematic analysis and identified a set of validation and identification techniques used by the participants for error prevention and recovery. The first research question (RQ 1 reported in Section 1.2) is answered by the findings of this study in conjunction with the findings of the previous retrospective study (reported in Section 3.1).

3.2.1 Methodology

3.2.1.1 Participants

We communicated with four schools belonging to two different states (Assam and West Bengal) of the North Eastern Region of India and sought prior permission from the school authority to conduct this study with the students abiding by the ethics of research. Before starting the study, we conducted a short semi-structured interview with potential participants. This interview served both as a means of data collection and a tool for purposive sampling. Participants with a prior understanding of geometric shapes and familiar with reading and drawing geometric shapes were selected for this study. Ten students (7 male and 3 female) between the ages of 15-18 (Mean = 16.78, SD = 1.09) participated in the study. All participants have prior experience of using mobile phones. Demographic information,

including the percentage and age of visual impairment of the participants and their level of prior practice of using the tactile board for drawing purposes, are presented in Table 3.2. We asked the participants to rate their level of prior practice (low, average, or high) of drawing on the tactile boards considering their frequency of prior practice and duration since the last practice.

Table 3.2: Demographic information of BLV participants.

Participant	Age	Gender	Visual impairment (%)	Impairment since	Class	Level of prior practice
P1	16	M	100	Birth	9	Low
P2	16	F	100	Birth	10	Average
P3	17	M	100	Birth	10	Low
P4	16	F	100	Birth	10	Low
P5	16	F	75	Birth	10	Average
P6	17	M	100	10 years old	10	Average
P7	18	M	100	3 years old	10	Average
P8	15	M	100	Birth	8	High
P9	18	M	75	Birth	10	Low
P10	18	M	100	Birth	10	Average

3.2.1.2 Apparatus

We communicated with ten schools (for students with visual impairment or blindness) belonging to ten distinct states located in different regions of India and found that the Taylor Arithmetic Slate (also called Taylor Arithmetic Frame, Taylor Slate, or Taylor Frame) (APH Collection, 2017) is the commonly used instrument for teaching geometric concepts. Although it is a teaching aid for arithmetic problem-solving, and Braille papers are also available for drawing, the advantage of innate tactile feedback and ease of modification are the primary reasons for using this instrument for teaching geometric concepts. We used this Taylor Arithmetic Slate (Figure 3.2) for both reading and drawing tasks. The instrument contains a rectangular metal sheet stamped with octagonal holes (typically an 18x25 grid) and placed on a wooden box. The wooden box also has a separate chamber for storing the metal pegs (also called types). The user needs to insert the pegs in the holes to operate the

instrument. A portion of the pegs protruding from the holes provide tactile feedback to the users.

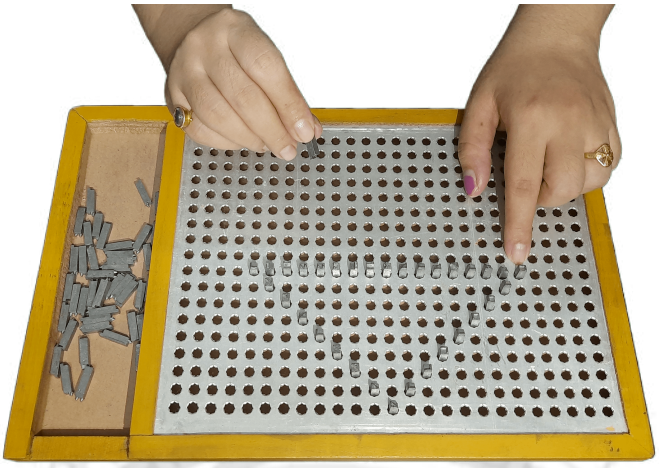


Figure 3.2: A user is drawing a triangle by inserting pegs with the right hand on a Taylor Arithmetic Slate containing an 18x25 grid of octagonal holes.

3.2.1.3 Task

The task requires the participants to draw two primitive geometric shapes and read a compound geometric shape on Taylor Arithmetic Slate (Figure 3.2). We selected two primitive geometric shapes - a triangle and a rectangle, which are most familiar to the students and frequently taught in the curriculum according to the teachers. Hence, we asked the participants to draw a triangle and a rectangle during the first part of the task.

Moreover, learning these two shapes is also helpful for recognizing bar graphs and line graphs. To read and draw these graphs using the selected primitive shapes, one must be able to read compound shapes formed by these primitive shapes. Therefore, in the second part of the task, a compound shape (Figure 3.3) containing a triangle and a rectangle was provided to the participants and asked to identify each shape and the shared edge.

3.2.1.4 Procedure

We conducted the study in classrooms of respective schools. During the experiment, the students were sitting in their usual seats, and the class teacher was also asked to be present during the experiment. The class teacher informed the students that this task was not a part of

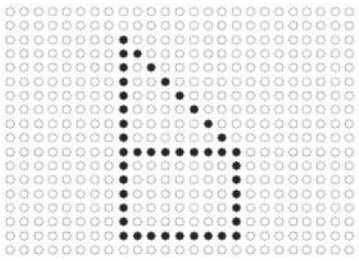


Figure 3.3: The compound shape provided for the reading task containing a triangle and a rectangle with a shared edge.

their academic evaluation. These particular arrangements were carried out to make the participants comfortable during the study. Each session was video recorded (without including faces) with the consent of the participants. Before starting the drawing task, a set of questions were asked to the participants to understand their familiarity with the geometry section in the course and theoretical and practical (tactile drawing) knowledge of triangles and rectangles. If a participant has a basic understanding of the triangle and rectangle, then the moderator verbally asks the participant to draw a triangle and a rectangle on the Taylor Arithmetic Slate. There was no specific requirement regarding the length of the edges and size of the angles (for triangles). The sequence of the shapes was altered for every next participant. No questions were asked to the participants during the task as it might distract the participants and increase their mental load. However, at the end of the task, questions were asked to understand the reason behind the indefinite hand movements and their goals. No help was provided while drawing except for cheering up the participants whenever they seemed to be lost in focus. The verbal encouragements were irrespective of the correctness of the drawings. There was no time limit, and the participants used their judgment to decide when the respective drawing was complete.

After completion of the drawing task, the participant was provided with a compound shape (Figure 3.3) and asked to identify each shape and the shared edge between the shapes. No questions were asked to the participants during the task to avoid distraction and increase in mental load. However, a few participants were voluntarily describing the steps involved in reading, and the outcomes of the steps followed. The drawing was rotated by 180 degrees (inverted) for every next participant. The only help provided was in terms of notifying that it was a wrong answer (one chance for each shape). However, at the end of the task, questions

were asked to participants to understand the reason behind indefinite hand movements and their goals. Participants took a maximum of 18 minutes to complete both drawing and reading tasks. The sequence of drawing and reading tasks was not altered as reading a shape drawn by the moderator may affect the mental model of the participants.

3.2.2 Findings

We analyzed the data collected during the direct observational study. Every smallest video segment containing a meaningful (goal-oriented) hand movement of the participants was recognized and coded (Garcez, Duarte, & Eisenberg, 2011). Meaningful hand movements were identified based on the results of the actions and supported verbal feedback. We also coded the transcribed verbal protocols of the participants. A total of 177 codes emerged as the first-level themes. Subsequently, the first-level themes that have an affinity to each other were grouped to form the second-level themes (outlined cards in Figure 3.4). Finally, we developed high-level themes (filled cards in Figure 3.4) from the second-level themes.

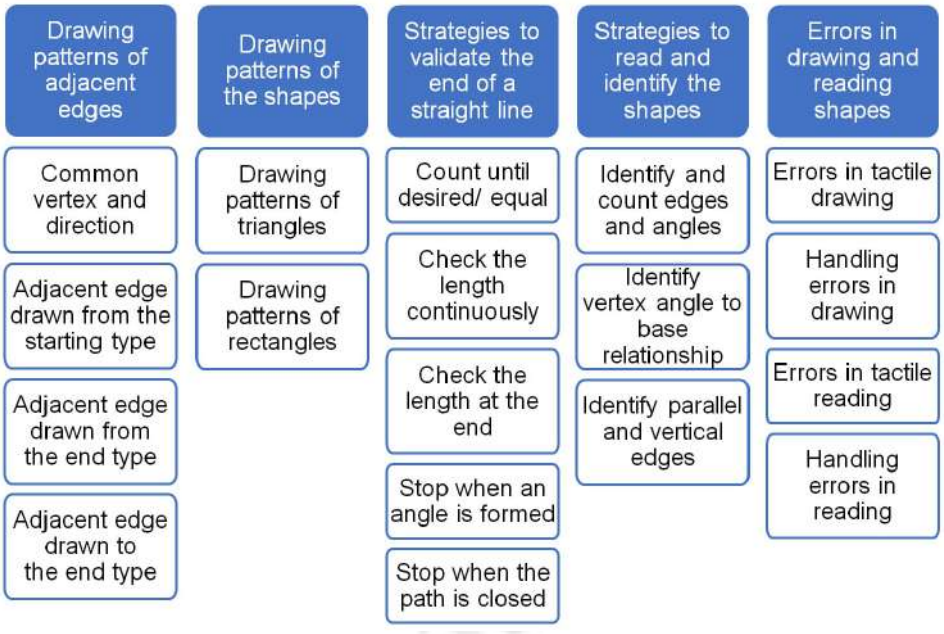


Figure 3.4: The high-level (filled cards) and second-level (outlined cards) themes emerged during analysis.

All the participants inserted the pegs or types (one at a time) in the appropriate holes to draw the desired shapes. For reading a shape, participants perceived the inserted pegs on the

tactile board by touching them with palms and fingers. The following subsections describe the patterns and strategies applied for drawing edges and shapes and the techniques of reading the shapes that emerged during the study. Finally, we describe the errors in drawing and reading the tactile shapes and the applied strategies for handling these errors.

3.2.2.1 Drawing patterns of adjacent edges

After drawing an edge, selecting the next hole (to be used as the starting point) for drawing the adjacent edge depends on the intended common vertex and the predetermined angle with the current edge. The grid-based arrangement of the holes on the Taylor Arithmetic Slate assisted the participants in selecting the correct hole (to be used) to produce an intended angle. Based on the intended common vertex, two patterns (rooted and linear adjacent edge) emerged for drawing an adjacent edge. However, a third pattern (converging adjacent edge) appeared while drawing the last edge of the shapes. In the following figure (Figure 3.5), a directed arrow represents the starting point and endpoint of drawing an edge, and the edge numbers represent the sequence of drawing the edges.

3.2.2.1.1 Rooted (or diverging) adjacent edge:

In this pattern, after the completion of an edge, the starting peg (point or type) of the current edge was selected as the intended common vertex. Then the adjacent edge was drawn from this common vertex. In this drawing pattern, the participants are often required to traverse back to the starting peg (point or type) of the current edge before drawing the adjacent edge. In Figure 3.5, edge-2 is a rooted adjacent of edge-1 (for both triangle and rectangle).

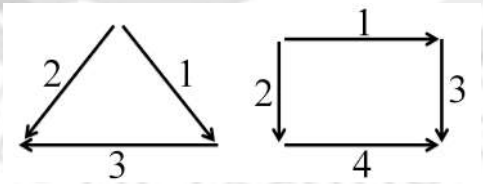


Figure 3.5: Drawing patterns of adjacent edges in a triangle and a rectangle.

3.2.2.1.2 Linear adjacent edge:

In this pattern, after the completion of an edge, the end peg (point or type) of the current edge

was selected as the intended common vertex. Then the adjacent edge was drawn from this common vertex. The majority of the participants did not use the linear drawing pattern for all the edges of the shapes. In Figure 3.5, edge-3 is a linear adjacent of edge-1 (for both triangle and rectangle), and for the rectangle, edge-4 is a linear adjacent of edge-2.

3.2.2.1.3 Converging adjacent edge:

In this pattern, after the completion of an edge, the end peg (point or type) of the current edge was selected as the intended common vertex. Then a line was drawn from a distant point to the common vertex as an adjacent edge. No participant drew an intentional converging adjacent edge that started from an abstract, distant point. However, the last edge of the shapes often appeared as the converging adjacent edge. As shown in Figure 3.5, for the triangle, edge-3 was drawn as a linear adjacent of edge-1 but appeared as a converging adjacent of edge-2. Similarly, for the rectangle, edge-4 was drawn as a linear adjacent of edge-2 but appeared as a converging adjacent of edge-3.

3.2.2.2 Strategies to validate the end of a straight line

The participants combined more than one of the following strategies and utilized them to validate the end of a straight line.

3.2.2.2.1 Validation by counting:

While drawing a straight line, the participants counted (in the head) the number of previously inserted pegs. This counting helped the participants to decide where to stop drawing a straight line with a predetermined length. This validation technique helped the participants to draw the first edge of a shape. However, the participants also employed this strategy to draw two lines of equal length.

3.2.2.2.2 Continuous validation of vertices:

The participants employed this strategy to draw two lines of equal length, where the participants had already drawn Line-1. Figure 3.6a and 3.6b showcase this approach for triangle and rectangle respectively. The participants compared whether the length of Line-2 was less than or equal to the length of Line-1. In this strategy, participants repeatedly

compared the two lines before adding a new peg to Line-2. This process was continued until the two lengths became equal.

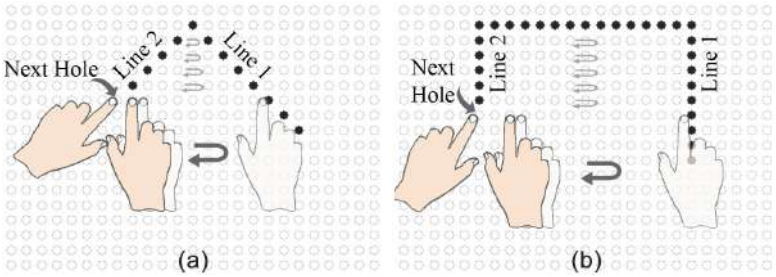


Figure 3.6: Continuous validation of vertices with the right-hand index finger to draw two lines (Line-1 and Line-2) of equal length in (a) triangle and (b) rectangle.

For this comparison, the participants kept the left-hand (majority) index finger on the next hole (to be used) of Line-2 and moved the right-hand index finger along a straight line expecting to meet a peg (intermediate or end) on Line-1. The participants repeated this process until the length of both the lines (Line-1 and Line-2) became equal. All the participants with a low level of prior practice followed this strategy to draw two lines of equal length.

3.2.2.2.3 One-time validation of vertices:

The participants employed this strategy to draw two lines of equal length, where the participants had already drawn Line-1. Figure 3.7a and 3.7b showcase this approach with the right-hand index finger respectively for triangle and rectangle. The participants compared the endpoints of the two lines (Line-1 and Line-2). Both the lines were confirmed to be of equal length if the endpoints form a straight line on virtually joining the holes between them. Unlike continuous validation, the comparison was made only once. Participants performed this validation technique when the count (in the participant's head) for Line-2 became equal to the count for Line-1.

To perform this comparison (as shown in Figure 3.7), the participants kept the left-hand (majority) index finger on the last inserted peg (or type) of Line-2 and moved the right-hand index finger along a straight line expecting to meet the end peg (point or type) of the Line-1. Meeting the end peg (point or type) of Line-1 confirms the validation of equal length.

As shown in Figure 3.8, another way of achieving this comparison was by placing the left-hand index finger on the last inserted peg (or type) of the Line-2 (Figure 3.8a for triangle and

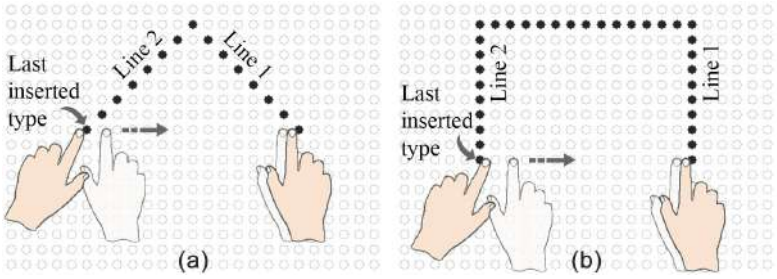


Figure 3.7: One-time validation of vertices with the right-hand index finger to draw two lines (Line-1 and Line-2) of equal length in (a) triangle and (b) rectangle.

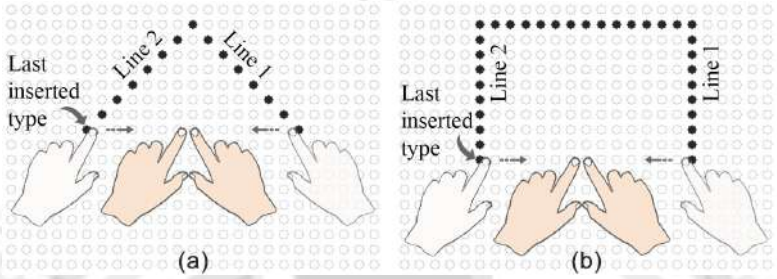


Figure 3.8: One-time validation of vertices with both index fingers to draw two lines (Line-1 and Line-2) of equal length in (a) triangle and (b) rectangle.

3.8b for rectangle) and by placing the right-hand index finger on the end peg (point or type) of the Line-1, and then the two fingers were moved towards each other expecting to meet around the middle of a straight line (virtual straight line joining the holes). Validation of equal length was confirmed if the two index fingers met each other. The participants with an average or high level of prior practice followed this strategy (with one or both hands) to draw two lines of equal length.

3.2.2.2.4 Angle validation:

Participants employed this strategy for drawing a line (current edge) that was intended to meet another line (adjacent edge) to form an angle. As shown in Figure 3.9, participants performed this validation right after inserting a peg (or type) that created the angle.

Participants compared the inclination of the adjacent edge with respect to the current edge. Here, the inclination of the adjacent edge was expected to be 90 degrees (for a rectangle or triangle, in Figure 3.9a) or 45 degrees (for a triangle, in Figure 3.9b). This strategy indicates the end of a line as well as confirms the correct progress in drawing an intended shape. None

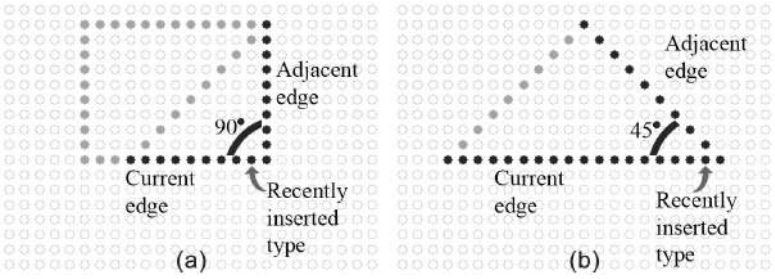


Figure 3.9: Angle validation by confirming the inclination of the adjacent edge with respect to the current edge. (a) 90 degrees for vertical and (b) 45 degrees for diagonal edges.

of the participants with a low level of prior practice used this strategy.

3.2.2.2.5 Closed path validation:

This strategy was applied for drawing the last edge of a shape. Participants continued drawing the last edge until the other end of the closed path (shape) was discovered as an adjacent peg (point or type). It was followed by the validation of the closed path by traversing the whole shape. However, this validation technique may not be reliable for drawing compound shapes.

Out of these five strategies mentioned above, the last three (One-time validation of vertices, Angle validation, and Closed path validation) comprise single-step validation. Participants performing these three validation strategies took comparatively less time than the first two strategies (Validation by counting and Continuous validation of vertices) as they involve multiple steps according to the size of the target shape.

3.2.2.3 Drawing patterns of the shapes

We recorded the participants' drawing patterns of triangles and rectangles and identified similar patterns among them based on the direction (starting point and endpoint) and sequence of drawing the edges. In the following patterns, a directed arrow represents the starting point and endpoint of drawing an edge, and the edge numbers indicate the order of the drawing's edges.

3.2.2.3.1 Drawing patterns of triangles:

We identified two patterns for drawing triangles that were followed by the majority of the participants. The identified drawing patterns are shown in Figure 3.10.

In these patterns, the first two edges (edge-1 and edge-2) were drawn either as rooted (in

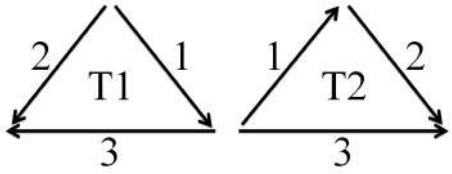


Figure 3.10: Two distinct drawing patterns of triangles.

T1) or linear (in T2) adjacent edges. For drawing the edge-1, all the participants used validation by counting with the intended length and direction. For drawing the edge-2, all the participants with an average or high level of prior practice employed the strategies of validation by counting and one-time validation of the vertices. The remaining participants majorly followed the strategy of continuous validation of the vertices. The edge-3 was drawn as either linear (in T1) or rooted (in T2) adjacent to edge-1. As a result, for both the patterns, edge-2 and edge-3 are converging adjacent edges. The majority of the participants employed the close path validation strategy for edge-3, except a few participants with an average or high level of prior practice employed the angle validation strategy.

3.2.2.3.2 Drawing patterns of rectangles:

We identified three patterns for drawing rectangles that were followed by the majority of the participants. The identified drawing patterns are shown in Figure 3.11.

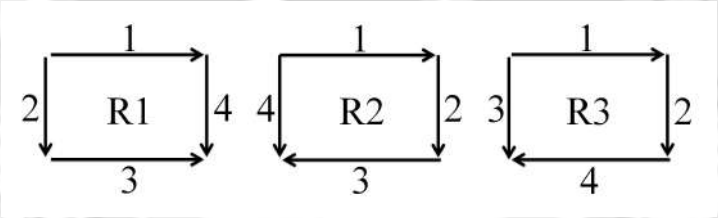


Figure 3.11: Three distinct drawing patterns of rectangles.

In these patterns, the first two edges (edge-1 and edge-2) were drawn as either rooted (in R1) or linear (in R2 and R3) adjacent edges. For drawing these two edges, all the participants used validation by counting with an intended length and direction. For the patterns R1 and R2, edge-3 was drawn as a linear adjacent to edge-2. As a result, edge-3 was parallel to edge-1. For pattern R3, edge-3 was drawn as a rooted adjacent to edge-1, and as a result, edge-3 was parallel to edge-2. For drawing the edge-3, all the participants with an average or high level

of prior practice employed the strategies of validation by counting and one-time validation of the vertices. The remaining participants followed the strategy of continuous validation of the vertices, along with validation by counting. The majority of the participants employed the close path validation strategy for edge-4. For all the patterns, edge-3 and edge-4 are converging adjacent edges.

3.2.2.4 Strategies to read and identify shapes

To read a shape on the Taylor Arithmetic Slate, participants need to perceive the inserted pegs with palms and fingers. As the inserted pegs represent the contour of the shape, the information regarding empty holes is also essential. Participants often utilized all the following strategies to identify the shapes. We did not find any preference in the selection of the following strategies concerning the level of practice of the participants.

3.2.2.4.1 By identifying and counting the edges and angles:

Participants identified the edges by moving the right-hand index finger over the pegs while the left-hand index finger was kept at the starting peg (point or type) or by placing the palms on the edges. Edges can also be identified by locating the vertices of a closed path (shape). Angles far from the shared edge (for compound shapes, Figure 3.3) were identified simply by locating the vertices with the palm (majority) or fingers. However, the majority of the participants further verified the presence and the type of angle by aligning two fingers (both index fingers or the thumb and index finger of the same hand) along the edges and interpreting the angular relationship between the two fingers. Angles adjacent to the shared edge were difficult to identify by touching with fingers or palm and by aligning with two fingers. These angles were identified by placing the fingers of both hands inside one of the closed paths (shapes) and by pushing the two edges of the angle in the downward direction. Identification of the angle was again made by interpreting the angular relationship between the fingers of one hand to another. This technique of placing the fingers of both hands in one of the closed paths (shapes) enabled the participants to relate the identified angle to that particular closed path (shape). These angles were further verified by moving the index finger over the two edges of the angle. Finally, a shape was identified by counting the number of angles and edges, and the types of angles (right angle or acute angle) found in a closed path (shape).

3.2.2.4.2 By establishing a relationship between an angle and an edge:

While trying to read the triangle, participants were trying to establish a relationship between the top angle (vertex angle) and the baseline. It was done by placing the index finger on the top angle and pushing the baseline towards the top angle with the thumb surface.

3.2.2.4.3 By establishing relationships between edges:

While trying to read the rectangle, the majority of the participants were trying to establish a relationship (parallel or vertical) between the edges. To identify parallel edges, the participants placed the thumb on one edge and the rest of the fingers on another edge and tried to move all five fingers (to and fro) along the edges. These two edges were confirmed to be parallel if the movements of the fingers were parallel (not diverging or converging). Vertical edges were identified by recognizing the right angles between them.

Moreover, participants were able to recognize the difference between the width and height of the rectangle without counting the number of pegs. It was accomplished by pushing opposite edges towards each other by the thumb and index finger (of the same hand) and comparing the span sizes (distances) between the two fingers. Some of the participants counted the pegs to verify the measurement perceived through span difference. The precision of perceived span difference is typically associated with the participant's level of practice.

3.2.2.5 Errors in drawing and reading shapes

All the participants had a basic understanding of the shapes (triangle and rectangle), which is essential for successful reading and drawing. However, all the participants made errors during both tasks. The majority of the participants were able to identify and recover the errors.

3.2.2.5.1 Errors in drawing:

The majority of the errors occurred due to the wrong selection of the adjacent hole that was going to be used to draw the target shape. Moreover, an increase in the time interval between the selection of the hole and inserting a peg contributed to inserting the peg in the wrong hole. The wrong perception of an axis of reference due to a rotation (unintentional) of the drawing board also resulted in selecting a wrong adjacent hole. Trying to draw an equilateral triangle on the grid often leads to an error as it requires skipping adjacent diagonal holes.

3.2.2.5.2 Handling errors in drawing:

Validation strategies were found to be helpful to prevent errors. The validation strategies often helped the participants to detect existing errors. In case of an error, identifying the error position and the error itself was troublesome, and a few participants failed to complete the task successfully even after the detection of an error. A few participants asked for sighted users' help in identifying the error position and the error. Continuous validation of vertices helped the participants to detect existing errors as well as identify the error position. Traversing the entire diagram and reviewing for errors by selecting adjacent positions for each previously inserted peg was found to be an effective recovery technique. However, the majority avoided this technique as it is a very laborious and time-consuming process.

3.2.2.5.3 Errors in reading:

Recognizing the vertices and angles on the shared edge was the most challenging part of reading a compound shape, as each of these vertices involves three different edges and two internal angles. Without recognizing the common edge as an overlapping of two edges belonging to two different shapes, the identification of both shapes becomes difficult. Moreover, according to the participants, a deviation of 45 degrees between two connected straight lines belonging to two different shapes (right edges of the compound shape in Figure 3.3) was also difficult to recognize only by touching with palms.

Instead of counting the pegs, differentiating between width and height based on span difference was not an effective method for the majority of the participants, particularly for the participants with a low and average level of prior practice. This span-based technique contributed to the error in distinguishing a rectangle from a square. For instance, one participant identified the shape as square, while after counting the number of pegs, it was concluded to be a rectangle.

It was observed for a few participants that a mismatch with an existing mental model of a geometric shape also resulted in wrong identification or failure. This mismatch was an issue with those participants who solely relied on matching perceived drawing with an existing mental model of a shape rather than incorporating any of the shape identification techniques. The most common reason for avoiding identification techniques was the difficulty in establishing relations among the edges and angles. One participant rotated the board

declaring that the provided figure had an inverted triangle. That participant was trying to match an existing mental model of a triangle comprised of one top angle and two base angles.

3.2.2.5.4 Handling errors in reading:

Application of the shape identification techniques on multiple components (edges, angles, shared edge, and closed paths) of the figure resulted in effective identification of the shapes. Knowledge of other shapes is also crucial as this helped the participants distinguish the target shape from others. For example, one participant said that the provided shape was not a rhombus as it had right angles (90-degree angles).

3.2.3 Discussion

The objective of this research is to understand the reading and drawing process of tactile geometric shapes, along with exploring the strategies for error prevention and recovery. The participants developed the mental model of the geometric shapes through tactile perception during their prior classroom training on tactile reading and drawing. Later, in the drawing task, the participants created the edges and the angles to represent their existing mental model of the shapes in the form of tactile drawings. Similarly, in the reading task, the participants identified the number of edges and angles and established the relationships among them to match the perceived tactile shape to the existing mental model of the shape. This process represented a blind person's tactile perception of real-world objects to develop the mental model and its tactile representation as reported in the literature (Kurze, 1996).

The majority of the participants with an average or high level of prior practice successfully read the compound shape without any help from sighted users and identified the shared edge between the primitive shapes. It indicates a successful spatial mental representation of both the primitive shapes (triangle and rectangle) and their overlapping edge. This finding aligns with the previous research that suggests that a high level of expertise in blind people (congenitally and early blind) may compensate for the impairment in spatial representation (Dulin, 2007).

Moreover, the strategies followed by the participants that emerged from the qualitative analysis of this research align with the properties (such as targeting an abstract point, evaluate the length of a line, and determine angles) of a successful drawing model proposed by Kamel & Landay, 2000. The participants performed two strategies, continuous validation

of vertices and one-time validation of vertices to draw two lines of equal length. Performing these strategies instantiates the property of "target an abstract point in relation to the drawing". Similarly, the strategies of validation by counting and measuring with the span of two fingers indicate the property of "evaluate the length of a line". Moreover, the angle validation strategy in drawing and identifying the angular relationships between the edges during reading indicates the implications of the property of "determine angles".

3.2.4 Recommendations

The findings of this study provided many useful insights into the tactile geometric drawing. We discuss these insights below in respect of the potential implications of developing a digital drawing tool.

3.2.4.1 Flexibility in selecting validation techniques

The selections of validation techniques differ across the participants based on their level of prior practice and percentage of visual impairment. A participant with a low level of prior practice often applied the continuous validation of vertices technique despite his 75% visual impairment. On the other hand, participants who had an average or high level of prior practice often applied the one-time validation of vertices and angle validation techniques regardless of their total blindness (100% visual impairment). We believe that a digital drawing tool must offer more than one validation technique to accomplish a task considering beginner, intermediate and expert user groups based on their percentage of visual impairment and level of practice. A similar inference can be drawn from the prior art, which mentioned that the understanding of drawing depends on the degree of vision and level of drawing practice (Vinter, Bonin, & Morgan, 2018).

3.2.4.2 Establishing relationships among the edges and angles

Reading a geometric figure involves identifying the edges and angles and establishing the relationships among them. Establishing the relationships among the edges and angles is the most challenging part of the shape identification process. For beginners, this information can be provided voluntarily (on the selection of the angles and edges) by the system to introduce

them to the relational concepts (parallel and vertical edges, the opposite edge of the vertex angle). The representation of these relational concepts can also be designed to meet the prior spatial knowledge of beginners. However, for intermediate and expert user groups, more natural interaction techniques can be provided to trigger the relational information. To enhance the spatial imagery of these user groups, the interactions must offer a metaphoric similarity with the conventional techniques of retrieving the relational information in the tactile drawing.

3.2.4.3 Easy traversing for effective error recovery

The participants often employed validation strategies for the prevention of errors during drawing. However, identification of the error position and recovery of the error required traversing the entire diagram. An easy and time-efficient traversing method could be useful in this scenario. A possible way to provide easy traversing would be to introduce milestones during the drawing (at each vertex or at custom positions). These milestones will divide the entire diagram into smaller segments for the ease of traversing the diagram with a reduced mental load.

3.2.4.4 Adequate feedback to explore the grid

The grid of holes on the Taylor Arithmetic Slate guided the participants throughout the drawing and reading process. The grid provided innate tactile feedback required to identify and select the intended holes and pegs. However, the majority of the errors in drawing occurred due to the wrong selection of the grid positions. These errors occurred as a result of the wrong perception of the axis of reference caused by a rotation of the drawing board, the selection of a grid position in the wrong direction, and the skipping of intermediate grid positions. In the literature, several digital drawing tools (Balik et al., 2013; Gorlewicz, Burgner, Withrow, & Webster III, 2014; Grussenmeyer & Folmer, 2016; Kamel & Landay, 2000; D. McGookin et al., 2010; Oh et al., 2013; Yu et al., 2003) followed this grid-based representation of the drawing space. We recommend that a grid-based digital drawing tool should provide adequate information on the selection of a grid position, such as any change in grid position, the current grid position, direction and distance with respect to the previous grid position, and information to relate to the current axis of reference.

3.2.4.5 Supporting both uni- and bi-manual interactions

All the participants (irrespective of the dominant hand) involved both their hands in reading and drawing tasks. The participants often used the left-hand index finger to mark a peg (point or type) of interest, count previously inserted pegs, and search and select the next hole to be used. In contrast, the participants often used the right hand to insert a peg and perform comparisons with previously inserted pegs. Moreover, for performing a complex task (one-time validation and interpretation of the angle with two index fingers), the participants used both hands to accomplish a single goal. Existing research on tangible graph creation (D. McGookin et al., 2010) also reported similar involvement of one or both hands for specific tasks. With this evidence, we recommend that in a digital drawing tool, the functions of reading and drawing (such as marking, counting and traversing the pegs, searching and selecting the holes, and validation techniques) should be mapped to the interactions with respective hand(s) and the system should support both uni- and bi-manual interactions.

3.2.5 Functions for designing a digital drawing tool

Based on the findings and our observations during pegboard-based drawing reported in previous studies, we identified several functions that could be potentially helpful in a digital tool to match the user's mental model of the existing pegboard-based drawing process. We categorized these functions into three levels such as basic, advanced, and smart functions. The basic functions are the functions that are essential to accomplishing the drawing task. At the same time, the advanced functions could cater to users to improve their performance by taking advantage of the digital platform. The smart functions could assist users during the drawing process by providing dynamic context-dependent features and feedback through an intelligent recommendation system. All these three categories of functions are reported in Table 3.3. Later in Section 5.1, during the participatory design study, we selected the basic and advanced functions for further refinement and mapping with bend gestures to design the bend gesture-based drawing tool (Naamya). In Section 5.2, for evaluation of Naamya, we implemented the basic functions and compared Naamya with a peg board-based drawing tool.

Table 3.3: The set of basic, advanced and smart functions identified after Study 1 and 2.

Function	Level	Description
Navigate FOCUS	Basic	Move FOCUS from one hole to another towards one of the eight directions.
Insert Peg	Basic	Insert a peg in the current hole in FOCUS.
Remove Peg	Basic	Remove the peg (if it exists) from the current hole in FOCUS.
Open Menu	Advanced	Open the vertical menu.
Close Menu	Advanced	Close the vertical menu if it is already open.
Navigate a List	Advanced	Vertically navigate a list of items towards the top or bottom.
Confirm	Advanced	Confirm the currently selected menu item or trigger YES.
Cancel or Reject	Advanced	Go back after cancelling the menu item selection process or trigger NO.
New Board	Advanced	Create a new empty virtual pegboard.
Open Board	Advanced	Populate a list of previously created boards.
Rename Board	Advanced	Rename the currently open virtual pegboard.
Save As	Advanced	Save the currently open virtual pegboard as a vector image.
UNDO	Advanced	Erase the last change done on the virtual pegboard.
REDO	Advanced	Restore the change that was undone.
Label a Grid Position	Advanced	Add an audio label to the current grid position (empty or filled) in FOCUS.
Clear All Pegs	Advanced	Remove all pegs and move FOCUS to Row 1 and Column 1.
Help	Advanced	Open a user guide.
Exit	Advanced	Exit from the drawing application.
Insert a Predefined Shape	Smart	Insert a predefined primitive shape from a list assisted by an audio description regarding the newly inserted shape's position, orientation, and intersection with other existing shapes.
Select a Labelled Shape	Smart	Automatically identify all the completed labelled shapes on the current board and populate a list of these labelled shapes along with the name of the shapes and position of the vertices, and a user can select a shape from the list.
Move the Selected Shape	Smart	Move the currently selected shape towards one of the eight directions and provide an audio description that explains how the newly moved shape will appear on the current board, including information regarding intersection with other existing shapes.
Copy the Selected Shape	Smart	Copy the currently selected shape and provide information regarding the shape's name, the position of the vertices, and its neighbouring shapes.
Paste the Copied Shape	Smart	Paste the recently copied shape closest to the top-left corner and provide an audio description that explains how the newly pasted shape will appear on the current board, including information regarding intersection with other existing shapes.
Relative Direction Information	Smart	Provide an audio description regarding the direction of a newly started line in relation to a previously drawn line. For instance, provide information regarding parallel, perpendicular, and the angle of inclined lines.
Relative Length Information	Smart	Provide an audio description regarding the length of a newly started line in relation to a previously drawn line. For instance, provide information regarding the number of pegs left to make them equal, already of equal length, and the number of pegs longer than another line.
Upcoming Intersection Information	Smart	Provide an audio description for a newly started line regarding where it will intersect if the user continues in the same direction. For instance, provide the grid position of an upcoming intersection with a vertex, the grid position of an upcoming intersection with a line, or no vertex or line to intersect ahead.
Recommendation for Direction Change	Smart	Provide an audio description recommending a change in the direction of progress of the current line at a particular grid position to create a closed shape.

3.3 Summary

This chapter reported the two studies of Phase I (Study 1 and Study 2). The findings of these two studies together answer the first research question (RQ 1 reported in Section 1.2). The first study reported in this chapter (Study 1 reported in Section 3.1) details the retrospective study conducted with students and teachers with blindness or low vision regarding mathematical diagrams. This study aimed to understand the experience of students and teachers in learning and creating mathematical diagrams and the need and scope for improvement through technological interventions in the Indian context. The second study reported in this chapter (Study 2 reported in Section 3.2) details the exploration of the existing geometric drawing tool used in schools in the Indian context and the strategies followed for reading compound geometric shapes and drawing primitive geometric shapes (rectangles and triangles). We conducted this direct observational study intending to understand the method of reading compound shapes and drawing primitive shapes (triangle and rectangle) to help design digital drawing tools that correspond to the user's mental model of using existing pegboard-based drawing tools. In the next chapter (Chapter 4), we aim to investigate bend gestures, which are easy to learn and perform and one of the commonly investigated types of deformation gestures. We intend to design the gesture space with additional descriptors of bend gestures (size and angle) and identify user-preferred bend gesture completion strategies. Considering the findings from this chapter (Study 1 reported in Section 3.1), which evidence that BLV students often take help from the sighted, we included both BLV and sighted users during the two studies (Study 3 and Study 4) reported in the next chapter. The reason to include sighted users is the potential need to assist BLV users during teaching and training. However, the contributions of this thesis are focused on the BLV user group only. Accordingly, the findings and observations concerning only the BLV user group are taken forward for the subsequent studies reported in this research work.

Chapter 4

Bend Gesture-based Interaction on Smartphone-sized Flexible Devices

The previous chapter (Chapter 3) presented two studies, including a retrospective study regarding mathematical diagrams and an exploration of the existing geometric drawing tool, along with the strategies followed for drawing. This chapter reports the two studies of Phase II (Study 3 and Study 4) that answer the second and third research questions (RQ 2 and RQ 3 reported in Section 1.2). We investigated bend gestures, which are easy to learn and perform and one of the commonly investigated types of deformation gestures. In this chapter, we intend to design the gesture space with additional descriptors of bend gestures (size and angle) and identify user-preferred bend gesture completion strategies. Considering the findings from the previous chapter (Section 3.1), which evidence that BLV students often take help from the sighted, we included both BLV and sighted users during the two studies of this Phase II (Study 3 and Study 4). The reason to include sighted users is the potential need to assist users with blindness or low vision during teaching and training. However, the contributions of this thesis are focused on the BLV user group only. Accordingly, the findings and observations concerning only the BLV user group are taken forward for the subsequent studies reported in this research work. The first study reported in this chapter (Study 3 including a preliminary Study) details the investigation of users' performance and preference for two magnitude levels of size and angle of bend as two additional descriptors of bend gestures. The second study reported in this chapter (Study 4) details the identification of user-preferred bend gesture completion strategies for discrete and continuous inputs.

4.1 Study on User Performance and Preference for Additional Descriptors of Bend Gestures

A user can perform bend gestures through manipulation of the physical form factor of the flexible device (Harrison et al., 1998; Kildal et al., 2012; S. S. Lee et al., 2010). These bend gestures are naturally associated with bending the flexible device at different locations and in two directions (upward and downward) (Lahey et al., 2011; S. S. Lee et al., 2010; Warren et al., 2013; Khalilbeigi, Lissermann, Kleine, & Steimle, 2012). According to the hierarchy of importance reported in the literature (Warren et al., 2013), the next most common higher-level descriptors of natural bend gestures are size (size of the bent area) and angle of bend. Exploring the size (Figure 4.1a) and angle (Figure 4.1b) as additional descriptors of bend gestures may offer promising results. Since bending the device at any location and direction already creates a certain magnitude level of size and angle, these two additional descriptors with one magnitude level do not contribute to gesture space. However, the size and angle as two additional descriptors with multiple magnitude levels can allow users to perform a larger set of distinct gestures with the same location and direction of bend.

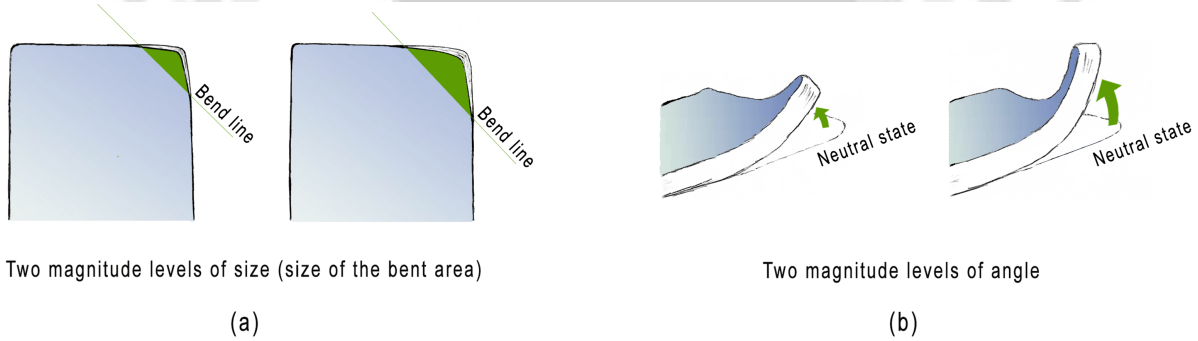


Figure 4.1: (a) Two magnitude levels of size and (b) two magnitude levels of angles performed at the same device location and direction.

With the use of sensors and computing devices, little changes in size and angle of bend can be detected. Since humans can not precisely detect all these little changes, before designing bend gestures with multiple magnitude levels of size and angle of the bend, it is crucial to understand the ease of differentiating among multiple magnitude levels, user performance, and preferences. In this section, we present a user study (including a preliminary study) to

investigate the user performance and preference for multiple magnitude levels of size and angle of bend gestures. The findings reported in this study (study 3 including a preliminary study) answer the second research question "RQ 2: How should the bend gesture space be designed using additional descriptors of bend (size and angle) considering the BLV user group's performance and preference?" (RQ 2 reported in Section 1.2).

4.1.1 Preliminary study on user performance and preference

This preliminary study aims to identify the participants' preferred number of magnitude levels for size and angle of bend irrespective of location and direction of bend gestures. We conducted this study with BLV and sighted participants performing bend gestures on a smartphone-sized flexible mock-up prototype.

4.1.1.1 Methodology of the preliminary study

4.1.1.1.1 Participants:

For participants with blindness or low vision, we communicated with two institutions seeking prior permission to conduct this study. We invited the students for their voluntary participation. The criteria for participation were to have a minimum of three years of experience using smartphones through touch gestures of screen readers (Google TalkBack or Apple VoiceOver), and their visual impairments (*Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018) are 70% or more with no upper limb disorder according to participants' medical certificates. Six students (4 male and 2 female) between the ages of 18-20 years (Mean = 18.83, SD = 0.98) participated in the study. All the participants use TalkBack. The participants' demographic information are presented in Table 4.1.

For the sighted participants, we invited university students of first-year for voluntary participation. The participation criteria were to have no upper limb disorder and a minimum of three years of experience in touch-based interaction with smartphones. Ten students (7 male and 3 female) between the ages of 18-20 years (Mean = 18.8, SD = 0.92) participated in the study. Except for two participants, all the other participants were right-handed. All BLV and sighted participants gave informed consent in advance to participate in this research work voluntarily and we followed the ethics of human subject research.

Table 4.1: Demographic information of BLV participants.

Participant	Age	Gender	Handedness	Visual impairment (%)	Impairment since	Perception of light
P1	20	M	Right	100	Birth	Yes
P2	18	M	Right	100	Birth	Yes
P3	20	M	Right	100	Birth	No
P4	19	F	Right	100	Birth	Yes
P5	18	M	Right	100	3 years old	Yes
P6	18	F	Left	100	5 years old	Yes

4.1.1.1.2 Apparatus:

The study was conducted using a flexible mock-up prototype (Figure 4.2) made of EVA (Ethylene-vinyl acetate) foam commonly known as expanded rubber or foam rubber of thickness 3 mm. The flexible mock-up prototype (Figure 4.2) measures 6.7 inches (170 mm) at the diagonal. The dimension of the prototype (154 mm x 74 mm) was decided to match the size of commonly used smartphones.

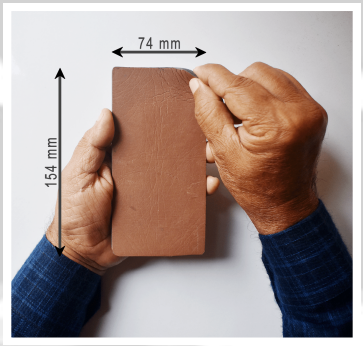


Figure 4.2: Smartphone-sized flexible mock-up prototype used for the preliminary study. Here the user is holding the flexible mock-up prototype with the left hand and performing the Top-right-corner Bend-upward gesture with the right hand.

4.1.1.1.3 Task:

In this study, we selected six bend gesture locations with two bend directions for performing bend gestures. These six locations comprised the four corners, the top side and the bottom side. We excluded the bend gestures at the right and left sides of the device (in portrait orientation), considering the associated difficulty in bending these sides. According to Lahey et al., 2011,

performing bend gestures on the entire longer sides of the device (left and right sides in portrait orientation) requires more physical effort, thus making them difficult to execute.

In this work, we represent the gesture locations, bend directions, and magnitude levels of the additional descriptors as hyphenated compound words. To refer to six device locations with two bend directions of the bend in a concise and meaningful way, we combined their names to present as location-direction pairs (a total of 12 location-direction pairs in Table 4.2). Again, to convey the gesture names meaningfully, we combined the names of the location-direction pairs (Table 4.2) with the magnitude level for the additional descriptor. For instance, if the user needs to perform a small angle bend at the Top-right-corner towards the upward direction, the gesture name conveyed to the participant is "Top-right-corner Bend-upward Small-angle".

Table 4.2: Twelve location-direction pairs obtained by combining six bend gesture locations and two bend directions. Here bending the device towards the user is called Bend-upward, and bending the device away from the user is called Bend-downward.

Gesture locations	Bend directions	Abbreviations of location-direction pairs
Top-right-corner (TRC)	Bend-upward (BU), Bend-downward (BD)	TRCBU, TRCBD
Top-left-corner (TLC)	Bend-upward (BU), Bend-downward (BD)	TLCBU, TLCBD
Bottom-right-corner (BRC)	Bend-upward (BU), Bend-downward (BD)	BRCBU, BRCBD
Bottom-left-corner (BLC)	Bend-upward (BU), Bend-downward (BD)	BLCBU, BLCBD
Top-side (TS)	Bend-upward (BU), Bend-downward (BD)	TSBU, TSBD
Bottom-side (BS)	Bend-upward (BU), Bend-downward (BD)	BSBU, BSBD

Since existing literature on bend gestures does not provide any measurable range or differences in terms of quantitative values that can differentiate small, medium, and large

magnitude levels, we asked the participants to perform these magnitude levels with minimal verbal instructions similar to that mentioned in the literature (Warren et al., 2013). We also asked the participants to define the magnitude levels (small, medium and large) by themselves so that they can clearly differentiate among the three levels and apply their own strategies to repeat the same differentiation in the future. No thresholds were assigned to these three (small, medium, and large) magnitude levels of size and angle. The only criteria for these three magnitude levels were that the second magnitude level (medium level) is higher than the first one (small level), and the third magnitude level (large level) is the highest among the three.

For each location-direction pair (Table 4.2), the participants were asked to perform the bend gestures repeatedly three times with three magnitude levels (small, medium, and large) of both size and angle of bend. For instance, if the first location-direction pair Top-right-corner Bend-upward (TRC-BU) of Table 4.2 is selected, then the participant first performs three bend gestures at the top-right corner location towards the upward direction. These three gestures are performed for three magnitude levels (small, medium, and large) of size. Then, the participants repeat these three gestures another two times. The same process was repeated for three magnitude levels of angle before moving to the next location-direction pair. The sequence of additional descriptors (size and angle) was counterbalanced, and the location-direction pairs were randomised across the participants.

4.1.1.1.4 Procedure:

The study was carried out in a controlled environment. First, the moderator described the objective of the study to the participants before starting the training session. We trained the participants in two consecutive training sessions. Out of these two sessions, the first session was focused on basic bend gestures without considering three magnitude levels of size and angle. We demonstrated the gestures for each of the twelve location-direction pairs of Table 4.2. We demonstrated the gestures to BLV participants by holding their hands. We assisted them in exploring the six gesture locations and two directions of bend. After introducing the locations and directions, we demonstrated and verbally explained how these bend gestures are performed for each of the twelve location-direction pairs. Then we asked all the participants to practice the gestures and familiarize themselves with the flexible prototype until they were

comfortable performing bend gestures on the prototype. Later in the second session, we trained the participants to interpret and perform bend gestures in terms of size and angle of bend. Again, during this session, we held the hands of the BLV participants to explain the size and angle of bend. After that, the participants were instructed to bend the target location with one hand while holding the device with the other hand. We informed the participants that the area of the bent surface is the size of bend and the extent of bend is the angle of bend. We further explained that the size of bend increases with the increase in the area of the bent surface (Warren et al., 2013). Similarly, the angle of bend increases with the increase in the extent of bend produced at the gesture location (corner or side) towards the bend direction, which is away from the neutral state. The participants were asked to practice three magnitude levels of size and angle of bend for each location-direction pair to reproduce them at the time of the preliminary study. During this practice, we did not help the participants unless they requested assistance or in case they were doing it incorrectly.

After completing the training, when the participants reported themselves as ready and comfortable to participate in the study, the moderator explained the task to each participant. Each participant performed three magnitude levels (small, medium, and large) of each additional descriptor (size and angle) three times for each location-direction pair. After performing all the gestures, we collected user preference data. We asked each participant to report their preferred number of magnitude levels based on individual performance in differentiating three magnitude levels irrespective of location and direction of bend gestures. We also asked them to share their experience in performing bend gestures with the two additional descriptors and their three magnitude levels.

4.1.1.2 Findings of the preliminary study

We analyzed the participants' preferences and verbal feedback. Both the participant groups reported no difficulty in understanding and performing bend gestures in terms of size and angle of bend as two distinct additional descriptors. However, the majority (100% BLV and 60% sighted) of the participants wanted to interpret different sizes of bend in terms of the distance of the bend line from the border of the location (corner or side) instead of the bent area of the flexible device. One BLV participant mentioned, "it will be easier to understand if" the moderators refer to it as a "distance of bend rather than size or size of bent area". One

sighted participant mentioned, “I am estimating distance from the border rather than the area since the area produced at corners and sides may be different, but I want to bend at a similar distance from the border”. We noticed that a similar interpretation of size in terms of distance from the border of the device was also considered in the literature for developing a functional prototype (Warren et al., 2013) with two bend sensors in pairs.

The majority of the participants reported difficulty in differentiating three magnitude levels of sizes (67% BLV and 70% sighted) and angles (83% BLV and 70% sighted) of bend. The participants mentioned that when they perform three magnitude levels, it becomes difficult to differentiate between them, which weakens their confidence in repeating the same set of magnitude levels of size and angle of bend. For the size of bend, one sighted participant mentioned, “I can easily perform two magnitude levels but bending a large section of the prototype requires more effort. But for the top and bottom sides, it is the small magnitude level which I found more difficult to bend by holding smaller area near the sides”. The BLV users also reported similar experiences. For the angle of bend, the medium magnitude levels create difficulty in distinguishing it from the other two (small and large). One sighted participant mentioned, “Sometimes I feel like the small magnitude level is very close to the medium, and if I increase the medium magnitude level, it gets closer to the large magnitude level, leaving a very small range for the large angle”. Another right-handed sighted participant mentioned, “I am unable to find any technique to remember the medium magnitude level of angle especially for the left corners”. One BLV participant mentioned, “I am able to differentiate three magnitude levels of angle. But I have to be very careful when I bend the device. During rush, the medium angle may touch the large angle”.

Both the participant groups also reported that differentiating three magnitude levels is not equally easy for each location-direction pair and they prefer to use only two magnitude levels irrespective of location and direction of bend gestures. Warren et al., 2013 also reported similar findings for a letter-sized deformable prototype. These findings further motivated us to conduct the following study on a smartphone-sized prototype to perform a detailed investigation of ease of differentiation, user performance, and preference for two magnitude levels of size and angle of bend for each location-direction pair.

4.1.2 Methodology

With the findings from the preliminary study reported in the previous Subsection 4.1.1, this main study aims to understand the ease of differentiating two magnitude levels of size and angle of bend and the user performance and preference for these two magnitude levels. We conducted this study with BLV and sighted participants in performing bend gestures on a smartphone-sized flexible prototype in portrait orientation.

4.1.2.1 Working definition of size and angle of bend gestures

In this study, we considered the size of the bend as the distance of the bend line from the border of the bent location (corner or side). We measured the perpendicular distance of the bend line from the border of the bent location (Figure 4.3a) to calculate the size of the bend. A similar approach was also reported in the literature (Warren et al., 2013) for developing a flexible prototype to detect three magnitude levels (small, medium, and large) of the size of the bend using two bend sensors in pairs. This process of measuring the size of bend gestures allowed users to interpret the size by estimating the distance of the bend line from the border of the location (corner or side) rather than estimating the area they need to bend.

Measuring size of the bend in terms of distance (x) from the border of the device
(a)

Measuring angle of bend in terms of angle (α) created by the bent surface with respect to the neutral state
(b)

Figure 4.3: Measuring the two additional descriptors of bend gestures. (a) The size of bend gestures is measured as the distance of the bend line from the border of the bend location, and (b) the angle of bend gestures is measured as the extent of the bend from the neutral state.

The bend angle is the angle created by the bent surface with respect to the relaxed or neutral state of the device. We measured the bend angles by drawing a tangent at the end of the bend

(where participants hold/push/pull the device with fingers) and measured its inclination from the relaxed position (Figure 4.3b). The terminologies such as bend line, bend angle, and the process of measuring bend angle are utilized from the literature (Systems, 2017).

4.1.2.2 Participants

For BLV participants, we communicated with two schools and sought prior permission from the school authorities to conduct this study. We invited the students for their voluntary participation. The participation criteria were to have a minimum of three years of experience using smartphones with touch gestures of screen reader (Google TalkBack or Apple VoiceOver), and their visual impairments (*Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018) are 70% or more with no upper limb disorder according to participants' medical certificates. Ten students (8 male and 2 female) without any other known disabilities between the ages of 18-22 years (Mean = 19.4, SD = 1.58) participated in the study. All the participants use TalkBack. The participants' demographic information are presented in Table 4.3.

Table 4.3: Demographic information of the BLV participants.

Participant	Age	Gender	Handedness	Visual impairment (%)	Impairment since	Perception of light
P1	18	M	Right	100	4 years old	Yes
P2	19	M	Right	100	Birth	No
P3	20	M	Right	100	19 years old	Yes
P4	18	M	Left	100	9 years old	Yes
P5	20	M	Left	100	Birth	Yes
P6	22	M	Right	100	Birth	Yes
P7	18	M	Right	80	11 years old	Yes
P8	18	F	Right	100	10 years old	Yes
P9	19	F	Right	100	Birth	Yes
P10	22	M	Left	100	Birth	Yes

For the sighted participants, we invited first-year university students for their voluntary participation. The participation criteria were to have no upper limb disorder and a minimum of three years of experience in utilizing touch-based interaction with smartphones. A total of

ten students (6 male and 4 female) without any known disabilities between the ages of 18-22 years (Mean = 19.6, SD = 1.26) participated in the study. Except for two participants, all the other participants were right-handed. Participants from both BLV and sighted groups had no prior experience of bend gesture-based interaction on a flexible device.

4.1.2.3 Experimental setup

We conducted the study in a controlled environment. Participants used one hand to hold the device and the other hand to perform the bend gestures while they were sitting and both forearms were resting on the table (Figure 4.4c). For this study, we used a smartphone-sized silicone-cast flexible prototype (Figure 4.4b). We followed a silicone cast fabrication process reported in the existing literature (Borah & Sorathia, 2022). The casting process was completed in three steps - pouring the initial layer of silicone in the bottom mold, placing the internal structure, and finally, pouring the second layer of silicone. The prototype measures 6.7 inches (170 mm) at the diagonal (154 mm x 74 mm) with a thickness of 6 mm. For both the BLV and sighted participant groups, we used this prototype in portrait orientation. The prototype comprises a flexible 3D-printed internal structure made of flexible TPU (thermoplastic polyurethane) sandwiched between two silicone-cast layers (Figure 4.4a). The shore hardness of the silicone is 25A, and the shore hardness of flexible TPU is 95A. We used flexible materials of lower stiffness to develop this prototype that resembles the deformable handheld prototypes reported in the literature (Lo & Girouard, 2014, 2017), as higher flexibility of the deformable device favours user comfort, performance, and user experience (Kildal, 2012; Kildal & Wilson, 2012; Lo & Girouard, 2014). The flexible 3D-printed internal structure (1 mm thickness) is used to hold the bend sensors and the wires connected to the sensors and the touchpoints. Four bi-directional bend sensors were placed along four corners of the prototype. The prototype's front side contains 32 (4 x 8) touchpoints made of conductive cloths. The wires connected to the bend sensors and touchpoints go out of the prototype as a single cable from the centre of the device's back (Figure 4.4c). The bend sensors and the conductive touchpoints are connected to an Arduino Mega microcontroller board. The microcontroller reads the bend and touch sensor inputs at a frequency of 20 Hz. In addition, the Arduino is connected to a smartphone via a Bluetooth shield. This Bluetooth connection with the smartphone allows the Arduino to trigger the

Google TTS (Text to Speech) Engine (Speech Rate=1.0 and Pitch=1.0) to speak out the gesture names. Each gesture name was mapped to a serial number, and the TTS engine speaks out the gesture name as soon as the respective serial number is entered.

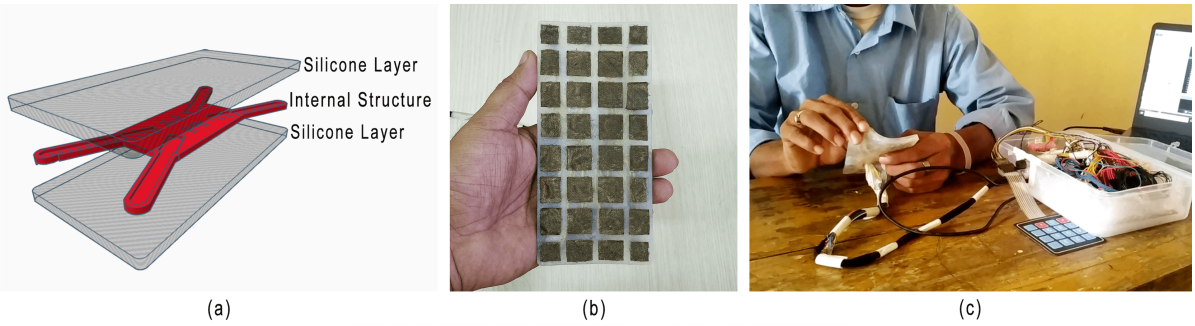


Figure 4.4: (a) The layers of flexible materials used in the prototype, (b) a participant is holding the prototype with the left hand, and (c) experimental setup for the user study.

The use of this functional prototype for this study is not to detect or recognize the bend gestures with two magnitude levels of size and angle of bend. Since existing research does not provide any threshold to detect two magnitude levels of size and angle of bend, we used this functional prototype to implement only an angle-based activation threshold and to utilize bend and touch sensor data to analyse user performance. We implemented an activation threshold of approximately 30 degrees (Lo & Girouard, 2017) for both upward and downward directions. Similar to existing literature ((Lahey et al., 2011; Daliri & Girouard, 2016)), the activation threshold of bend allowed us to avoid unwanted or unintended bend gestures by providing a range of angles that the system could ignore. We used this threshold during both training and the user study to help participants perform bend gestures with angles larger than 30 degrees. No feedback was provided on crossing the activation threshold considering that it might affect user performance and to avoid any potential bias. However, after the bent location reaches its relaxed position, one non-verbal audio feedback (beep sound) was provided to indicate that the last gesture was valid and recorded successfully. Otherwise, the user performs the same gesture again with a larger degree of bend. This activation angle majorly helped us during the training session. We also wanted to understand how users hold the bent location while performing the bend gestures with different magnitudes of size and angle. For this purpose, we recorded the bend and touch sensor data.

To measure the values of bend gestures accurately, only the bend sensor's readings are not

sufficient as these readings are combinations of size and angle (Warren et al., 2013). In addition, sensor readings may also vary depending on their placement in the prototype. Since this study aims to understand user performance during different sizes and angles of bend, no fixed or predefined bend line was provided to the participants. As these bend lines may vary across the participants, fixed marker-based tracking was not applicable in this scenario. Therefore, in this work, we measured the values for two levels of size and angle of bend from captured images using Kinovea (Version 0.8.15), a 2D (two dimensional) motion analysis software (Puig-Diví et al., 2019). Although the measurements obtained from Kinovea software are accurate for a perspective of 90-45 degrees, we captured the images or recorded the videos from an approximately 90-degree angle with respect to the direction of bend as suggested in the literature (Puig-Diví et al., 2019). It was done by changing the position of the camera, as shown in Figure 4.5. For angles of bend, the camera position (position A-H of Figure 4.5b) was changed with respect to the participant's hand grip, gesture location, and gesture direction. However, the camera position was not changed until a participant performed both angle-based gestures for a particular location-direction pair. As measuring angles is challenging on an occluded and vertical setting (Steimle et al., 2013), we positioned the camera parallel to the surface of the device for recording angles (Figure 4.5b) and vertically above the surface to record the size of bend (Figure 4.5a).

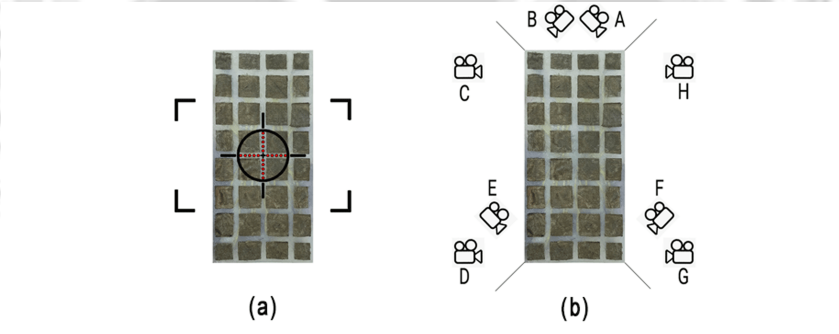


Figure 4.5: Different camera positions to measure (a) size of bend gestures and (b) angle of bend gestures .

4.1.2.4 Task

We asked the participants to perform two magnitude levels of both size and angle of bend at each gesture location and direction. We used 12 location-direction pairs (6 locations x 2

directions in Table 4.2) to explore size and angle of bend gestures. For instance, the Top-right-corner (TRC) location and the Bend-upward (BU) direction together is a location-direction pair (TRC-BU) at which participants performed two magnitude levels of size and angle of bend. We asked the participants to perform each magnitude level three times before they rated the ease of differentiating small and large magnitude levels of an additional descriptor (size and angle) for a location-direction pair. After completion of two magnitude levels for both size and angle of bend for a location-direction pair, the participants reported their preference for two magnitude levels of size and angle of bend for that location-direction pair. Participants were also asked to share their rationales or strategies that allowed them to differentiate two magnitude levels of the additional descriptors. We also asked them to share their experience regarding the ease of differentiating two magnitude levels with respect to different locations and directions of bend.

4.1.2.5 Procedure

We started with the training session after the moderator described the objectives of the study to the participants. The participants first practised the basic bend gestures (without considering multiple magnitude levels of size and angle) for the twelve location-direction pairs of Table 4.2. Then we trained the participants to interpret and perform bend gestures in terms of size and angle of bend. After that, the participants were instructed to bend the target location with one hand while holding the device with the other hand. We informed the participants that the distance of the bend line from the border of the location (corner or side) determines the size of the bend. On the other hand, the angle of bend is measured in terms of the extent of the bend. We demonstrated how the participants could change the size and angle of bend at one of the location-direction pairs. For BLV participants, the demonstration involved assisting the participants (by holding hands) in holding the gesture location, positioning fingers to decide the size and bending the device to a different extent to change the angle. This way, the moderator assisted each participant in performing four gestures. For the rest of the pairs, the participants carried out the bend gestures by themselves unless they requested assistance or if they were doing it incorrectly. The location used for the demonstration was randomized across the participants.

For both participant groups, no thresholds for the two magnitudes (small and large) or

external feedback methods were provided to differentiate and perform two magnitude levels of size and angle of bend. This particular arrangement was made to investigate user performance in deciding the magnitude levels, repeating the same without any external feedback method and strategies applied to repeat the gestures. However, a non-verbal audio feedback (beep sound) was provided on releasing the bend gesture to indicate that the last gesture has crossed the activation threshold of the bend sensors. After the training session, the moderator explained the task to each participant. The TTS (Text To Speech) engine speaks the gesture name and after the buzzer plays the first beep sound, the participant starts the bend gesture. After crossing the activation threshold, when the bent location is released back to its neutral state a second beep sound is played. This audio feedback (beep) confirms that the last gesture has successfully crossed the activation threshold. The participants performed each gesture three times with an intermediate period of 10-15 seconds. During this intermediate period, the participants were asked to release the device entirely to force them to develop a strategy to remember and repeat the bend gesture. We were aware of the fact that the grid of touchpoints may influence the performance of both participant groups, as these touchpoints can be used as tactile and visual markers. To minimize this influence, we asked the participants to mention their own rationales or strategies for differentiating two magnitude levels that do not involve the touch grid.

4.1.2.6 Data collection method

After performing two magnitude levels of size for a location-direction pair, participants rated the ease of differentiating these two magnitude levels of size on a 5-point Likert scale (1 being very difficult and 5 being very easy). The same process was repeated for two magnitude levels of angles. Participants also reported their preferences for two magnitude levels after performing both size and angle-based gestures for the same location-direction pair. The participants who did not prefer two magnitude levels were further asked to report their preference for one of the magnitude levels (small or large) or none. We asked the participants to verbally share their experience to understand the rationales or strategies of differentiation, the reason for that strategy, any other difficulties in performing or repeating the gestures, and the ease of differentiation with respect to the location and direction of bend gestures. This process was repeated for each gesture location and direction selected for this study (Table 4.2). We randomized the location-direction pairs and counterbalanced the

sequence of additional descriptors (size and angle) across the participants. However, all participants performed the small magnitude level before performing the large magnitude level.

4.1.3 Results

In this study, we aimed to investigate the use of two additional descriptors along with two basic descriptors. The two basic descriptors of bend gestures are location (four corners, top side, and bottom side) and direction of bend (upward and downward). The two additional descriptors are size and angle of bend with two magnitude levels (small and large). Each of the 20 participants performed 48 distinct gestures (6 locations x 2 directions x 2 additional descriptors x 2 magnitude levels) and each gesture was repeated three times. Participants rated on a 5-point Likert scale for ease of differentiating two magnitude levels (1 being very difficult and 5 being very easy) and mentioned their preference for the magnitude levels of size and angle of bend. This gives us 480 Likert scale ratings and 2880 measured values for size and angle of bend using Kinovea software. Before analyzing the collected data, we carried out the Shapiro-Wilk test (Shapiro & Wilk, 1965) on the data collected for ease of differentiating the two magnitude levels. This test is a hypothesis test used on a sample to determine if it follows a normal distribution. We found that the collected data (ease of differentiation) are not normally distributed. Therefore, to interpret the collected data, we applied non-parametric tests, the Friedman and Wilcoxon Signed Rank (WSR) tests. We also calculated agreement scores (as defined by Wobbrock, Aung, Rothrock, & Myers, 2005 and utilised in Wobbrock, Morris, & Wilson, 2009) to understand the consensus among the participants towards the preferences for size and angle-based bend gestures.

4.1.3.1 Findings from reported ease of differentiation

We conducted a WSR test to compare the ease of differentiating size with respect to the angle of bend. We found a significant difference only for the BLV participant group. For them, differentiating two magnitude levels of size was significantly easier than angles for Top-right-corner Bend-upward (Z=-2.070, p=0.038), Top-right-corner Bend-downward (Z=-2.121, p=0.034) and Top-left-corner Bend-downward (Z=-2.264, p=0.024). Except for these three, there was no significant difference at any given location and direction. We also

compared the ease of differentiating two magnitude levels between the two participant groups. Results indicate that only size differentiation for Top-right-corner Bend-upward (Z=-2.271, p=0.023) and Top-left-corner Bend-downward (Z=-2.050, p=0.040) was found to be significantly easier by BLV participants than sighted participants. We conducted the Friedman test on ease of differentiating two magnitude levels among the location-direction pairs. We found a significant difference for the ease of differentiating two magnitude levels of size (p=.001 for BLV and p=.041 for sighted) and angle (p=.007 for BLV and p=.0002 for sighted) of bend across the location-direction pairs. We did not run any additional statistical tests to compare the ease of differentiating between two magnitude levels of size and angle between various location-direction pairs in order to control the family-wise error rate and to prevent the increased likelihood of type II errors through Bonferroni adjustments (Perneger, 1998).

4.1.3.2 Consensus among the participants

We calculated agreement scores (Wobbrock et al., 2009) to evaluate the consensus among the preferences of the participants. The following Table 4.4 presents the agreement score (AS) and the preferences of both participant groups. We found higher (more than 0.5) agreement scores for both size and angle of bend at all four corners towards upward and downward directions for BLV participants and only towards upward direction for sighted participants. For the top and bottom sides, we found higher (more than 0.5) agreement scores for only size differentiation towards upward and downward directions for BLV participants and only upward direction for sighted participants. In addition, for the BLV group, we found higher (more than 0.5) agreement scores for two magnitude levels of angle for Top-side Bend-upward and Bottom-side Bend-downward. For all higher agreement scores, the majority (60% or more) of the participants from each group preferred to use two magnitude levels of the additional descriptors (Table 4.4).

Table 4.4: Preferences of both the participant groups for two magnitude levels of size and angle of bend. In this table, each row under a participant group column represents the Agreement Scores (AS) for the participant groups and the number of participants that preferred both, none, small and large magnitude levels of the additional descriptor for a given location-direction pair.

Location-direction pairs	Additional descriptors	BLV participants					Sighted participants				
		AS	Both	None	Small	Large	AS	Both	None	Small	Large
Top-right-corner	Size	1	10	0	0	0	0.82	9	0	0	1
Bend-upward	Angle	1	10	0	0	0	0.58	7	0	3	0
Top-right-corner	Size	0.68	8	0	2	0	0.34	5	2	1	2
Bend-downward	Angle	0.82	9	0	1	0	0.42	5	1	4	0
Top-left-corner	Size	1	10	0	0	0	0.66	8	0	1	1
Bend-upward	Angle	0.82	9	0	0	1	0.58	7	0	3	0
Top-left-corner	Size	1	10	0	0	0	0.3	4	2	1	3
Bend-downward	Angle	0.54	7	0	2	1	0.42	4	1	5	0
Bottom-right-corner	Size	0.82	9	1	0	0	0.66	8	0	1	1
Bend-upward	Angle	1	10	0	0	0	0.54	7	2	1	0
Bottom-right-corner	Size	0.54	7	1	2	0	0.34	5	1	2	2
Bend-downward	Angle	0.54	7	1	2	0	0.3	3	2	4	1
Bottom-left-corner	Size	0.66	8	0	1	1	0.52	7	1	1	1
Bend-upward	Angle	0.82	9	0	1	0	0.54	7	2	1	0
Bottom-left-corner	Size	0.68	8	0	2	0	0.3	4	1	2	3
Bend-downward	Angle	0.68	8	0	2	0	0.38	3	2	5	0
Top-side	Size	0.82	9	0	1	0	0.54	7	1	0	2
Bend-upward	Angle	0.82	9	1	0	0	0.42	6	1	1	2
Top-side	Size	0.58	7	0	3	0	0.28	4	2	2	2
Bend-downward	Angle	0.42	5	1	4	0	0.26	3	2	3	2
Bottom-side	Size	0.58	7	0	3	0	0.68	8	0	0	2
Bend-upward	Angle	0.46	6	0	3	1	0.34	5	2	2	1
Bottom-side	Size	0.58	7	0	3	0	0.3	4	2	1	3
Bend-downward	Angle	0.52	6	0	4	0	0.36	2	4	4	0

4.1.3.3 Findings from measured values of size and angle of bend

To investigate the participants' performance in performing two magnitude levels of additional descriptors (size and angle), we analysed the values of size and angle of bend which are measured using the Kinovea software.

4.1.3.3.1 Variability in repeating gestures:

As the participants were asked to repeat the same magnitude level of size and angle of bend using their own strategy, we first measured the variability in the three repetitions of the gestures. For each magnitude level of size and angle of bend, we measured the number of participants against each location-direction pair (presented in Table 4.5) who performed the repetitions with variability more than the range of 10 mm for size and 10 degrees for angle. We selected a range of 10 mm for size-based gestures, which is approximately half of the width of the thumb (I. ISO, 2008). For angle-based gestures, we selected a range of 10 degrees, considering its use as an activation threshold in the literature (Kildal, 2012).

We found that out of twenty-four size-based gestures (12 location-direction pairs x 2 magnitude levels of size), 25% of them have at least one BLV participant who crossed the range of 10 mm. In contrast, none of the sighted participants have crossed the range of 10 mm for small and large magnitude levels of size. We also noticed that for size-based gestures performed by the BLV group, all the cases where variability in small magnitude level is higher than large magnitude level are associated with sides of the device. This indicates the difficulty in performing small magnitude levels of size-based gestures on the sides (top and bottom sides in portrait orientation) by holding a small section of the flexible device.

Out of twenty-four angle-based gestures (12 location-direction pairs x 2 magnitude levels of angle), the majority (83.3% for small angle and 100% for large angle by BLV group and 100% for both small and large angle by sighted group) have at least one participant who crossed the range of 10 degrees. In addition, the total number of participants who crossed the range of 10 degrees has increased by 47.6% for the BLV group and 74.3% for the sighted group while performing a large magnitude level in comparison to a small magnitude level of angle.

Table 4.5: Number of participants who crossed the range of 10 mm for size-based gestures and 10 degrees for angle-based gestures.

Location-direction pairs	BLV participants				Sighted participants			
	Range > 10 mm		Range > 10 degrees		Range > 10 mm		Range > 10 degrees	
	Small size	Large size	Small angle	Large angle	Small size	Large size	Small angle	Large angle
Top-right-corner Bend-upward	0	1	3	3	0	0	1	6
Top-right-corner Bend-downward	0	1	0	3	0	0	5	3
Top-left-corner Bend-upward	0	0	3	4	0	0	4	7
Top-left-corner Bend-downward	0	0	1	3	0	0	4	3
Bottom-right-corner Bend-upward	0	0	2	4	0	0	3	5
Bottom-right-corner Bend-downward	0	0	2	2	0	0	1	3
Bottom-left-corner Bend-upward	0	0	3	2	0	0	5	4
Bottom-left-corner Bend-downward	0	0	1	1	0	0	4	7
Top-side Bend-upward	0	0	0	3	0	0	3	6
Top-side Bend-downward	1	0	3	2	0	0	1	6
Bottom-side Bend-upward	2	0	2	2	0	0	1	6
Bottom-side Bend-downward	2	1	1	2	0	0	3	5

4.1.3.3.2 False large magnitude levels of size and angle-based gestures:

The values for two magnitude levels of size and angle-based gestures measured using the Kinovea software indicate that although participants reported performing large magnitude level, a few times (1.9% of times for size and 4.1% of times for angle by BLV participants and only 2.2% of times for angle by sighted participants) the actual measured value for the large magnitude level is less than or equal to the small magnitude level performed by the same participant. We refer to a gesture as a false large magnitude level when the measured value for at least one of the three repetitions of the reported large magnitude level is less than or equal to one of the three measured values for the small magnitude level performed by the same participant at the same location and direction of bend.

Table 4.6: Number of participants who performed false large magnitude levels.

Location-direction pairs	BLV participants		Sighted participants	
	False large size	False large angle	False large size	False large angle
Top-right-corner Bend-upward	1	1	0	1
Top-right-corner Bend-downward	0	1	0	0
Top-left-corner Bend-upward	0	3	0	0
Top-left-corner Bend-downward	0	1	0	0
Bottom-right-corner Bend-upward	1	1	0	0
Bottom-right-corner Bend-downward	0	0	0	1
Bottom-left-corner Bend-upward	0	2	0	2
Bottom-left-corner Bend-downward	0	2	0	1
Top-side Bend-upward	0	0	0	2
Top-side Bend-downward	1	3	0	0
Bottom-side Bend-upward	3	1	0	1
Bottom-side Bend-downward	1	0	0	0

In Table 4.6, we present the number of participants who performed false large magnitude levels for size and angle of bend against each location-direction pair. We found that out of twelve location-direction pairs, the false large magnitude levels for size-based gestures were identified for 42% and 0% of the pairs by BLV and sighted groups, respectively. For angle-based gestures, false large magnitude levels were identified for 75% and 50% of the location-direction pairs by BLV and sighted groups, respectively. Although both participant groups

were trained to perform size and angle-based gestures, we also noticed that the participants often tend to hold a larger section of the flexible device while going to perform a large angle bend. It is found to be more common for top and bottom sides.

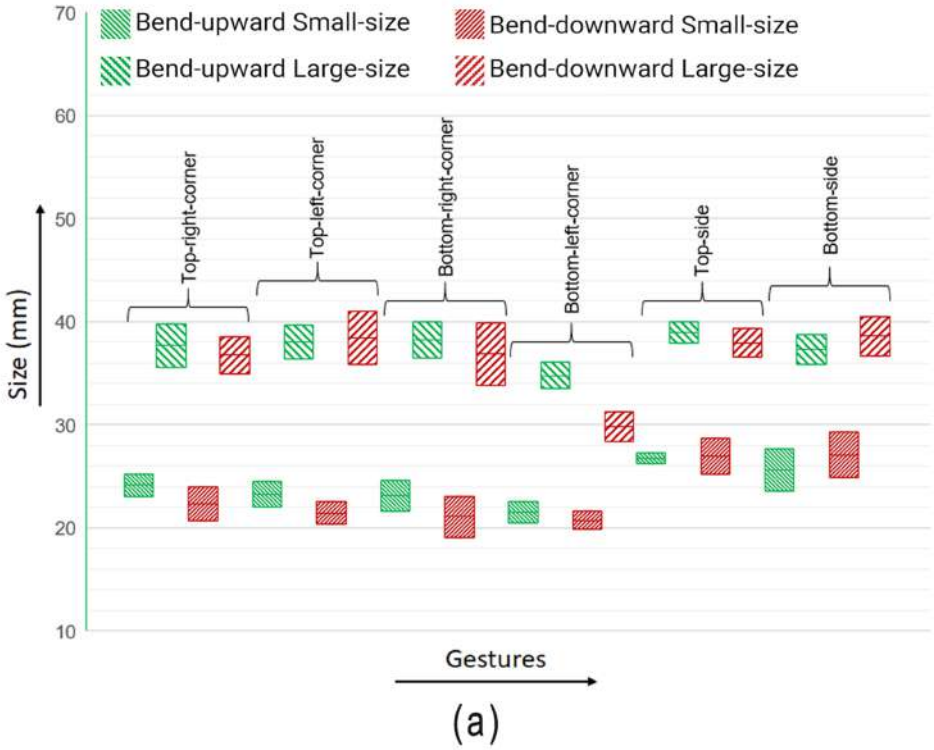
4.1.3.3.3 Failures in crossing activation threshold and the grip on the device:

We also analysed the data regarding the number of times the participants failed to cross the activation threshold. We found that during the user study, 2.8% and 5.3% of failed attempts were made to cross the activation threshold by BLV and sighted groups, respectively. All the participants were requested to repeat the gesture for each failed attempt. We also noticed that the number of failed attempts had decreased during the user study as compared to the training session. The average failure in crossing the activation threshold for all the location-direction pairs has decreased by 79% and 72% for the BLV and sighted groups, respectively. This indicates the ease of learning bend gestures by both user groups. In addition, we noticed that the total number of failures in crossing the activation threshold for the downward direction is higher than the upward direction. This also indicates the difficulty in bending towards the downward direction as compared to the upward direction.

We also analyzed the activated touchpoints during interaction and found that bottom-corner bend gestures often activate more touchpoints as compared to top-corner gestures due to the grip on the device. This indicates more occlusion of the device during bottom-corner gestures.

4.1.3.3.4 Confidence intervals for size and angle of bend:

Since each participant performed the gestures three times, we collected a total of 60 values (30 values from each participant group) for each magnitude level of size and angle of bend for a given location-direction pair. We identified the outliers using the 1.5 interquartile range (IQR) rule (Tukey, 1977). After removing the outliers, we calculated the 99% confidence intervals for each magnitude level of size and angle of bend at each location-direction pair for both BLV (Figure 4.6) and sighted (Figure 4.7) participant groups. As shown in Figure 4.6a and 4.7a, we found no overlapping between the small and large magnitude levels of size-based gestures for any given location-direction pair. However, we found smaller differences (less than 10 mm) between the small and large magnitude levels of size for 4 location-direction pairs by the BLV group (Bottom-left-corner Bend-downward, Top-side Bend-downward, Bottom-side Bend-upward, and Bottom-side Bend-downward gestures in Figure 4.6a) and 1 location-direction pair by the sighted group (Bottom-left-corner Bend-downward in Figure 4.7a).



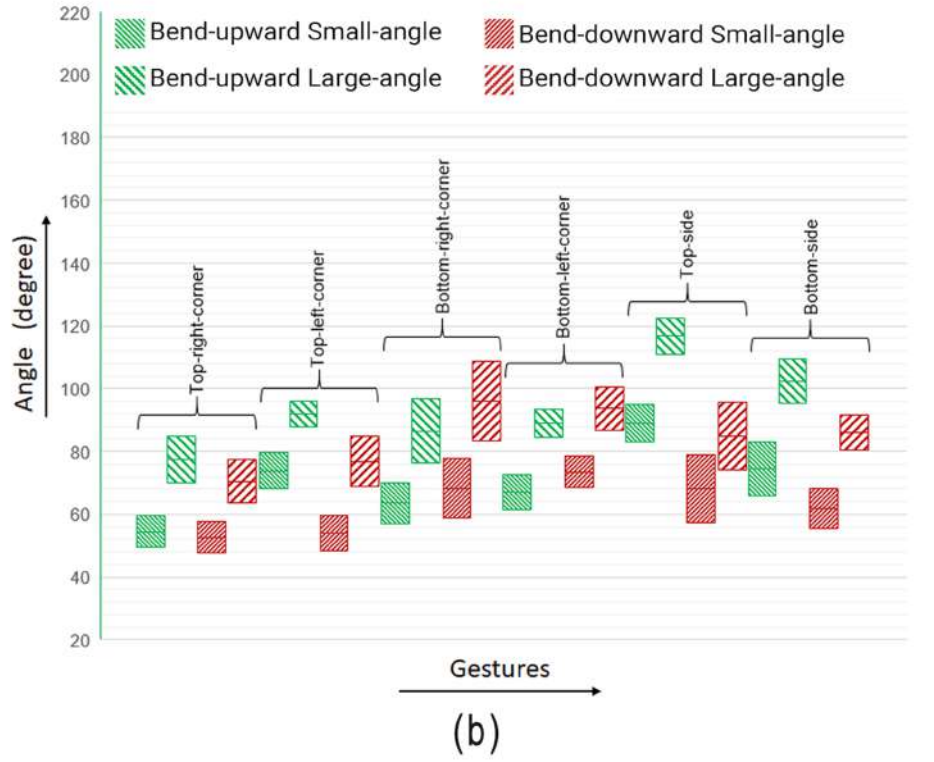
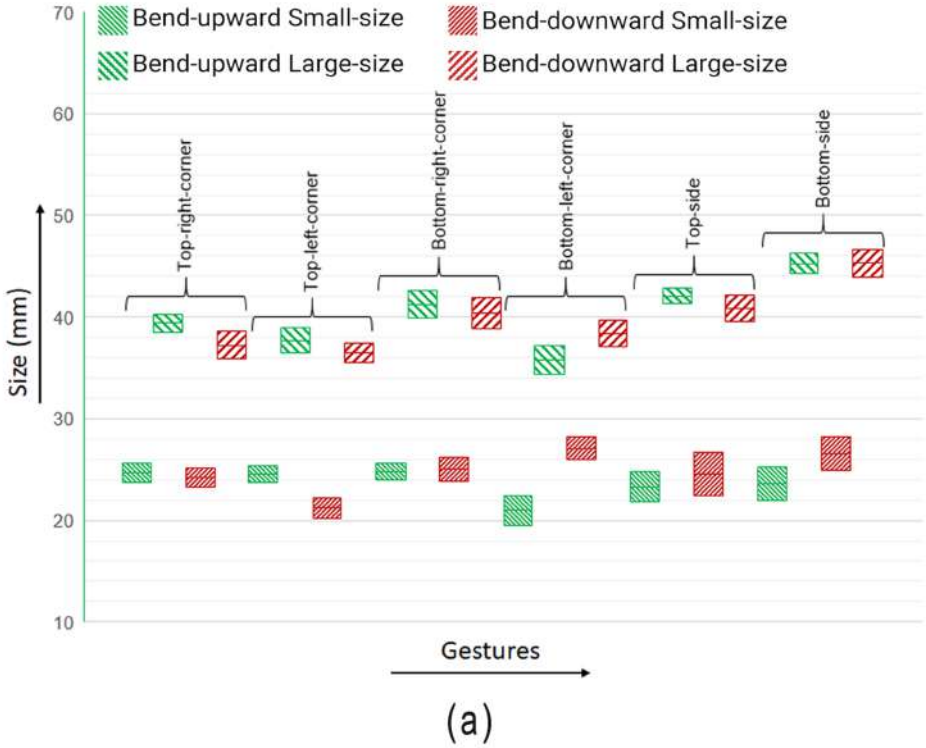
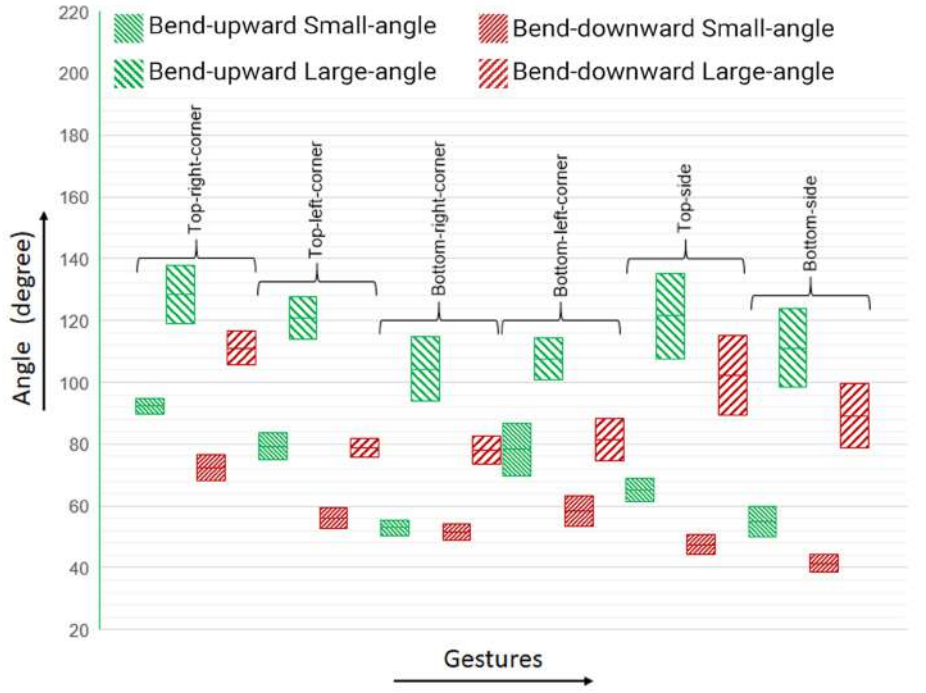


Figure 4.6: For the BLV group, confidence intervals for the population mean in performing two magnitude levels of (a) size and (b) angle of bend for different location-direction pairs. (Coloured Figure)



(a)



(b)

Figure 4.7: For the sighted group, confidence intervals for the population mean in performing two magnitude levels of (a) size and (b) angle of bend for different location-direction pairs. (Coloured Figure)

For small and large angles of bend (for any given location-direction pair), there is no overlapping between the intervals for sighted participants (Figure 4.7b). However, for the BLV group, there is an overlapping between the intervals of small and large levels of angle for the Top-side Bend-downward (Figure 4.6b). Furthermore, we found smaller differences (less than 10 degrees) between the small and large magnitude levels of angle for 5 location-direction pairs (Top-right-corner Bend-downward, Top-left-corner Bend-upward, Bottom-right-corner Bend-upward, Bottom-right-corner Bend-downward, and Bottom-left-corner Bend-downward gestures in Figure 4.6b). We also noticed that the overlapping and the majority of the smaller differences between small and large magnitude levels (80% for size and 60% for angle) occurred for the downward direction of bend.

We also calculated the confidence intervals for the population mean for BLV and sighted groups irrespective of location-direction pairs. We found smaller differences (less than 10mm for size and 10 degrees for angle) between the two participant groups for both small and large magnitude levels of size (Figure 4.8a) and angle (Figure 4.8b). This indicates comparable performance by the two participant groups when reviewed, irrespective of the location and direction of bend gestures.

Figure 4.8: Confidence intervals for the population mean for BLV and sighted groups in performing two magnitude levels of (a) size and (b) angle of bend irrespective of location and direction of bend. (Coloured Figure)

4.1.3.4 Findings from participants' verbal response

We collected and investigated the participants' verbal descriptions to identify the strategies for differentiating two magnitude levels of size and angle of bend. We also analyzed the verbal feedback shared by the participants regarding the ease of differentiating two magnitude levels of size and angle of bend for different location-direction pairs.

4.1.3.4.1 Strategies for differentiating two magnitude levels:

Performing two magnitude levels of size-based gestures requires the participant to decide the approximate bend line before performing the gesture and hold the flexible device appropriately. As a result, differentiation of two magnitude levels of size-based gestures takes place before initiating the gestures. In contrast, participants from both groups often hold the flexible device at the same position before performing any of the two magnitude levels of angle. As a result, performing two magnitude levels of angle-based gestures initiates similarly and differentiation takes place during progress.

For differentiating two magnitude levels of size (Figure 4.9a), the BLV participants reported using tactile sense to estimate the finger movement from the border of the device to differentiate two magnitude levels and to perform large magnitude levels. They first identify the location (corner or side) and hold the device comfortably closer to the border to perform the small magnitude level of size-based gestures. For a large magnitude level of size-based gesture, the participants first identify the location (corner or side) and then move their fingers towards the centre of the device. According to the participants, this finger movement is made by a distance approximately equal to the width of the thumb. According to them, their tactile sense and spatial ability assisted them in estimating the required distance to repeat the same gesture three times. Participants also preferred continuous contact with the device surface to estimate the traversed distance more accurately. In addition, this continuous contact with the device offers them higher confidence during the interaction. For differentiating two sizes of bend, the sighted participants applied a similar strategy as that of BLV participants (Figure 4.9a). The majority of them directly estimated finger position from the border of the device via visual perception to perform the small and large magnitude levels of size-based gestures. However, they reported difficulty in positioning their finger for large magnitude level of downward bend gestures. For downward bend gestures, the index finger movement was estimated based on its

relative position with respect to the thumb (placed on the device's front surface). According to the majority of the BLV (80%) and sighted (70%) participants, the intended finger movement for performing a large magnitude level was approximately equal to the thumb's width.

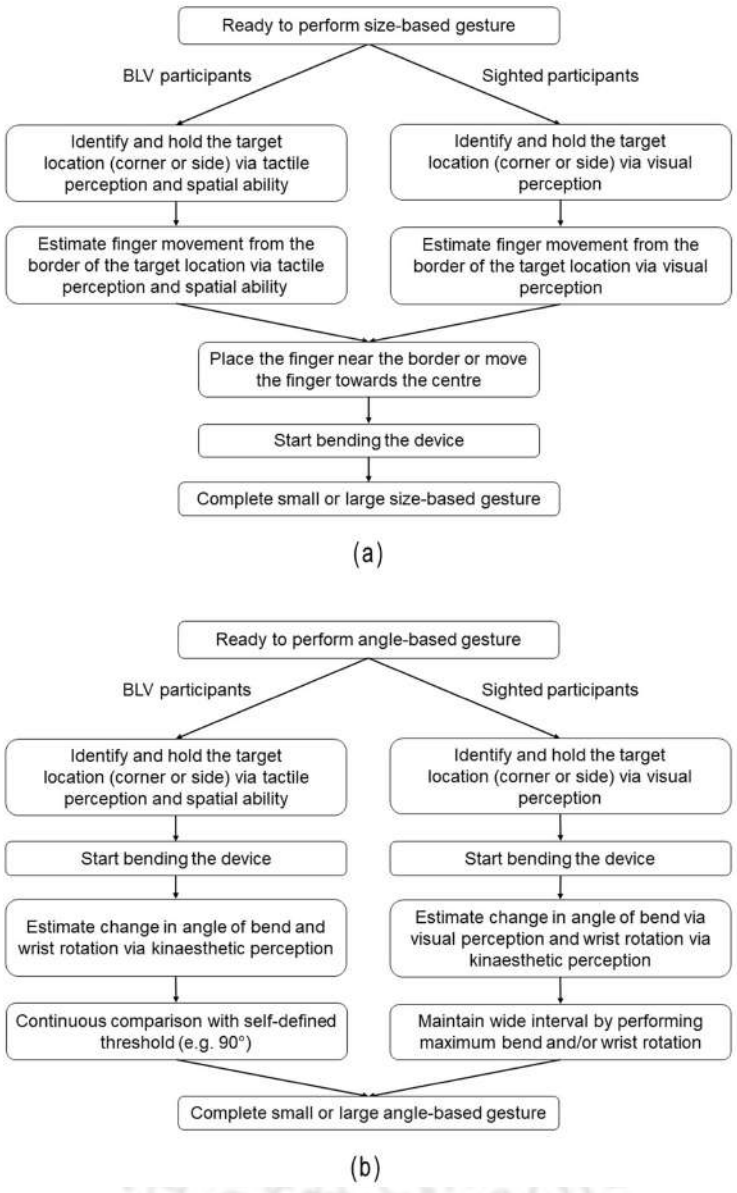


Figure 4.9: Strategies followed by the two participant groups to differentiate two magnitude levels of (a) size and (b) angle.

For differentiating two magnitude levels of angle (Figure 4.9b), the BLV participants reported using kinesthetic perception to estimate the device bend and wrist rotation. They mentioned that they could easily estimate the difference in the rotation if they could hold and

bend the device comfortably and naturally. Only two BLV participants explicitly mentioned that they could perceive when the angle of bend is approximately 90 degrees, which they used as a threshold to differentiate small and large magnitude levels of angle. All the sighted participants applied a safe approach for differentiating two magnitude levels of angle, where the two magnitude levels were often separated by a wide interval (Figure 4.9b). For instance, the small magnitude does not touch the bending finger, while for a large magnitude, participants tend to perform maximum bend that either touches the bending finger or the opposite surface. According to the sighted participants, having a wide interval offers ease of differentiation and less probability of mistake as it is difficult to estimate the angles by looking at the bend. They also mentioned that this type of differentiation is easy only if the flexible device allows users to perform large angles naturally without any difficulty.

4.1.3.4.2 Ease of differentiating two magnitude levels at different locations and directions:

We also analyzed the participants' verbal feedback to identify and calculate the number of participants who verbally reported similar responses regarding ease of differentiation for different locations and directions of bend. According to the majority of the BLV participants, differentiation of two magnitude levels at corners are easier than sides (70% of participants for size and 80% of participants for angle-based gestures). According to them, angle differentiation at the top and bottom sides of the device becomes difficult due to the associated effort required to produce a large magnitude level of angle. On the other hand, size differentiation at the top and bottom sides of the device becomes difficult due to the associated difficulty in bending a small size by holding a small section of the device. This resulted in holding a relatively larger section of the device for small size-based gestures (Figure 4.6a). According to them, the differentiation of two magnitude levels at the Top-right-corner is easier than the Top-left-corner (all right-handed participants, that is, 70% of participants for both size and angle-based gestures) and bottom corners (80% of participants for size and 70% of participants for angle-based gestures). They also mentioned that the differentiation of two magnitude levels at the Top-left-corner is easier than the bottom corners (70% of participants for both size and angle-based gestures), the Top-side is easier than the bottom corners and bottom-side (70% of participants for both size and

angle-based gestures), and the upward direction is easier than the downward direction (70% of participants for size and 60% of participants for angle-based gestures).

According to the majority of the sighted participants, differentiation of two magnitude levels at corners are easier than sides (80% of participants for both size and angle-based gestures). According to them, angle differentiation at the top and bottom sides of the device becomes difficult due to the associated effort required to maintain a wide interval between two magnitude levels. On the other hand, size differentiation at the top and bottom sides of the device becomes difficult due to the associated difficulty in bending a small size by holding a small section of the device. According to them, the differentiation of two magnitude levels at the Top-right-corner is easier than the Top-left-corner (all right-handed participants, that is, 80% for both size and angle-based gestures) and bottom corners (90% of participants for both size and angle-based gestures). They also mentioned that the differentiation of two magnitude levels at the Top-left-corner is easier than the bottom corners (60% of participants for both size and angle-based gestures), the Top-side is easier than the bottom corners (60% of participants for only size-based gestures) and Bottom-side (70% of participants for only size-based gestures), and the upward direction is easier than the downward direction (70% of participants for size and 60% of participants for angle-based gestures).

4.1.4 Discussion

We analyzed the results obtained from statistical analysis, the consensus among participants' preferences, participants' actual performance and their verbal responses. In this section, we discuss the results in the following subsections considering the additional descriptors of bend gestures, differentiation of two magnitude levels, and preference and performance of the two participant groups in differentiating two magnitude levels of size and angle of bend at different locations and directions. We also proposed a set of design recommendations for selecting bend gestures considering the target user group.

4.1.4.1 Distinguishing size and angle of bend

During the study, both participant groups reported no difficulty in distinguishing the additional descriptors (size and angle) as two different descriptors of bend gestures. However, during the

training phase, initially, participants from both groups reported difficulty in distinguishing size and angle of bend. Similar findings were also reported in the literature for sighted participants where they found difficulty in distinguishing the concepts of size (size of the bent area) and angle of bend (Warren et al., 2013). During training, we observed that the major confusion was associated with small magnitude levels of size and angle of bend. One likely reason could be the similarity between the inclination generated during the small magnitude level of size and angle-based gestures. In this context, one participant mentioned, "I feel performing the same bend gesture for both small size and small angle of bend". Although participants were able to distinguish between size and angle during the study, there are certain drawbacks of using both size and angle-based gestures in the same scenario. One drawback is that the user can perform angle-based bend gestures (small or large) by holding either a small or large size of the flexible device. This may create ambiguity during gesture recognition. In addition, we observed that participants often tend to hold a larger section of the flexible device while performing a large angle bend. One participant realized the mistake and mentioned, "When I perform a bend gesture by holding a larger section of the device, it often gives me a wrong perception of performing large angle bend without enough rotation of my wrist". In such cases, these types of gestures may create further confusion for the users as a user might get a wrong perception of completing a large angle-based gesture while it has lead to ambiguity (the system recognized both large size and large angle) or wrong input (the system recognized only large size instead of large angle). This also leads to a similar logical conclusion of using either size or angle of bend as recommended in the literature (Warren et al., 2013).

4.1.4.2 Strategies for differentiating two magnitude levels of size and angle of bend gestures

The strategies followed by the participant groups (Figure 4.9) indicate the application of tactile and kinesthetic perception by the BLV group and majorly visual perception by the sighted group. Both participant groups reported that they were able to differentiate two magnitude levels of size and angle of bend using the reported strategies. The process of size differentiation takes place before initiating the bend gesture and the angle differentiation takes place while the bend gesture is in progress. As a result, user attention is required before performing the size-based gestures to decide the finger position on the device. In contrast,

continuous user attention is required during the progress of angle-based bend gestures to continuously perceive and estimate the angle of bend. This need for longer continuous attention during two magnitude levels of angle-based gestures contributed to participants' higher preferences toward size-based gestures (Table 4.4). In addition, if the finger position is correctly decided for sized-based gestures, then there is less scope for providing wrong input while a size-based bend gesture is in progress. On the other hand, for angle-based gestures, users may end up bending large magnitude levels instead of small magnitude levels or may have a wrong perception of performing large angles due to lack of attention. We believe this need for continuous attention could be one of the reasons for the higher number of variability (Table 4.5) and false large magnitude levels (Table 4.6) for angle-based gestures by both the participant groups. The sighted participants also mentioned that performing two magnitude levels of angles requires more physical effort than two magnitude levels of size as a large angle of bend demands more device bending and wrist rotation. One sighted participant mentioned, "Angle of bend estimation requires more focus and differentiation of two magnitude levels needs continuous attention. A wide interval between two magnitude levels makes it easy to differentiate at the cost of more effort in bending large angles. Having a narrow interval will increase the errors because, during rush, I might end up bending large angles every time". We believe another reason for a higher number of variability for angle-based gestures (Table 4.5) could be the higher flexibility of the current prototype. According to literature (Kildal & Wilson, 2012), soft deformable devices are easier to bend, but it is difficult to maintain a constant angle of bend. Conversely, the use of a hard device will make it difficult to perform large angles, which will again create difficulty for the sighted group to maintain a wide interval between small and large magnitude levels of angle-based gestures. However, changing the device's flexibility may not have a similar effect on differentiating two magnitude levels of size-based gestures provided the entire device is equally flexible or bend line positions for small and large magnitude levels are equally flexible.

To differentiate two magnitude levels of size, both the participant groups applied a similar strategy of estimating the finger movement for performing large magnitude levels. According to both participant groups, the intended finger movement is approximately equal to the width of the thumb. In Figure 4.8a, for size-based gestures, the maximum difference between

confidence intervals of small and large magnitude levels of BLV (14.4mm) and sighted (16.7mm) group are approximately two-thirds of the highest anthropometric measurements for the width of the thumb (the 95th percentile for men) (Pheasant & Haslegrave, 2018). One likely reason for being close to two-thirds of the width of the thumb is when the user initially touches the border of the device to perform a small magnitude level of size, usually, the surface of the thumb touches the border rather than aligning the edge of the thumb with the border of the device. Moreover, due to the application of similar strategies by both the participant groups for size-based gestures, we can observe similar separation patterns of confidence intervals for BLV (Figure 4.6a) and sighted (Figure 4.7a) groups. Although both groups apply similar strategies, BLV participants prefer continuous contact with the device for higher confidence during input. One BLV participant mentioned, "Since we do the measurements by touching with fingers and palms, a continuous contact with the device surface offers higher confidence during interaction". Similar findings were also reported in the literature (Borah, Sorathia, & Sarcar, 2021). However, this continuous contact with the device surface during finger movement may trigger touch gestures for touch-sensitive flexible devices. Such multi-modal interaction with touch-sensitive flexible devices requires further investigation. We also noticed that as sighted participants were solely dependent on visual perception, for downward bend gestures, the index finger movement was estimated based on its relative position with respect to the thumb (placed on the front surface of the device). We believe this lack of direct visual feedback during downward bend gestures contributed to the lower number of preferences of sighted users for downward bend gestures (Table 4.4). Despite this lack of visual feedback, we found no variability (Table 4.5) and no false large size-based gestures (Table 4.6) by sighted participants. This indicates the potential use of downward bend gestures by both participant groups with appropriate feedback.

For angle-based gestures, the BLV group applied their kinesthetic perception to estimate small and large magnitude levels of angle with self-defined thresholds (for instance, two participants mentioned 90 degrees). In contrast, the sighted group maintained a wide interval to differentiate small and large magnitude levels of angle. According to sighted participants, estimation of small changes in angle is difficult and having a wide interval offers ease of differentiation and more confidence in avoiding performance errors due to overlapping measures of angles. This difference in strategies resulted in closely and widely separated

confidence intervals of BLV (Figure 4.6b) and sighted (Figure 4.7b) groups, respectively. For maintaining a wide interval between small and large magnitude levels, the sighted participants often performed maximum bend that either touches the bending finger or the opposite surface. However, similar to fold gestures, bend gestures with maximum bend partially occludes the display. Warren et al., 2013 also reported the use of smaller bend gestures for minimum screen occlusion. Avoiding such large magnitude levels of angle-based gestures results in narrow intervals (between small and large magnitude levels of angle) that lead to difficulty in differentiating two magnitude levels of angle by sighted participants. We also believe that the strategies for angle-based gestures do not contribute towards preserving consistency in repeating angles of bend, which resulted in a higher number of variability (Table 4.5) by both participant groups. Overall the findings of this study indicate that the strategies followed by the two participant groups and their channel of perception influence their performance and preference for two magnitude levels of size and angle of bend.

4.1.4.3 Preference and performance with respect to location and direction of bend gestures

In terms of location, both participant groups reported higher preferences for both size and angle-based gestures (with two magnitude levels) at all four corners and for only size-based gestures (with two magnitude levels) at the top and bottom sides of the device (Table 4.4). In terms of direction, the BLV participants reported higher preferences for both upward and downward directions of bend and the sighted participants preferred only upward direction (Table 4.4). According to both participant groups, angle differentiation at the top and bottom sides of the device becomes difficult due to the associated effort required to produce large magnitude level of angle-based gestures. One BLV participant mentioned, "Usually, I hold a small section of the device at corners to perform both magnitude levels of angle. However, it is difficult for the sides to perform large angles by holding a small section of the sides. Likewise, bending a larger section of the device for large angle bend also requires more effort". Similar feedback was also provided by a sighted participant, "Performing maximum bend or very large bend at sides requires more effort as I have to hold the entire side of the device". This associated effort resulted in a lower preference for angle-based gestures at the top and bottom sides of the device. A few participants also reported difficulty in performing

small size-based gestures by holding a small section of the side. One BLV participant mentioned, "I can differentiate two magnitude levels of size on the top and bottom sides. However, instead of having two magnitude levels (small and large), I will prefer to have only the large magnitude level for sides along with bending the device at the middle (along the horizontal axis)". One sighted participant also proposed a similar middle bend or fold gesture in addition to a large magnitude level of size-based gesture on the top and bottom sides. Similar bend gestures along the horizontal axis at the middle of the device are also reported in the literature (Ernst & Girouard, 2016a; Ernst et al., 2017). Furthermore, we believe the difference in the consensus of the two groups regarding the direction of bend is due to different applied channels of perception for differentiation strategies and the difficulties associated with the downward bend direction. According to literature, bend gestures towards the downward direction are difficult to perform as compared to upward bend gestures (Warren et al., 2013; Girouard et al., 2015). We also noticed similar difficulties experienced by both the participant groups, which led to a higher number of failures in crossing the activation threshold during the study for downward directions. However, this difficulty in performing bend gestures towards the downward direction has no major effect on the preferences of BLV participants as their angle differentiation strategy does not require a wide interval between the two magnitude levels of angle and for size differentiation, they were dependent on tactile feedback. One BLV participant mentioned, "All the students of our school will find it easy to differentiate two levels of size and angle". When we asked about the reason behind that comment, the participant answered, "We have experience in identifying objects by touching". In this regard, another BLV participant mentioned, "If this type of device becomes available, we will need less time to learn the interactions as compared to touchscreen devices". This is analogous to the findings of prior research (Ernst et al., 2017). For the sighted group, the angle differentiation requires a wide interval between the two magnitude levels of angle and they primarily depend on visual perception for both angle and size-based gestures. However, the difficulty in performing large angle-based gestures towards the downward direction does not allow for maintaining a wide interval, which eventually leads to difficulty in differentiating two magnitude levels of angle towards the downward direction. In addition, for downward bend gestures, the lack of direct visual estimation of finger position (for size) and device rotation (for angle) made it difficult for the

sighted group to differentiate two magnitude levels of size and angle of bend.

During the study, both participant groups reported no difficulty in distinguishing the additional descriptors (size and angle) and were able to differentiate two magnitude levels of each additional descriptor. However, their performance was not identical across all the locations and directions of bend. Similarly, we also found statistically significant differences in the ease of differentiating two magnitude levels of size and angle of bend across the location-direction pairs (Subsection 4.1.3.1). According to both participant groups' verbal feedback, differentiating two magnitude levels of size and angle of bend at the top locations (Top-right-corner, Top-side and Top-left-corner) are easier than the bottom locations. They also reported that differentiating two magnitude levels at corners is easier than sides and the upward direction is easier than the downward direction. A higher number of failures in crossing the activation threshold towards the downward direction also indicate the difficulty in downward bend gestures. We also found that the majority of the small differences between the confidence intervals of small and large magnitude levels of size and angle of bend and the overlapping angle of bend are associated with the downward direction. We also noticed that for both participant groups, size-based gestures at top corners are free from overlapping and small differences between small and large magnitude levels. We also observed that both the participant groups performed skewed bend gestures by bending uneven lengths on the associated edges. During the study, we observed that the skewness was caused by a non-uniform movement (movement not along the bisector) of the fingers towards the center of the device. These skewed bend gestures were more common at bottom corners and sides. One BLV participant also reported the need for physical markers for ease of recognising bend lines to perform small and large size-based gestures. The use of physical markers in the form of grooves on a flexible device was also found to be helpful in literature (Ernst et al., 2017). Overall the findings indicate that the ease of differentiating two magnitude levels and user preference and performance of the two participant groups change with respect to location and direction of bend.

4.1.5 Design recommendations

Based on the findings from this work, we report a set of recommendations for designing bend gesture-based interaction for only BLV users and both BLV and sighted users.

4.1.5.1 Use of size-based gestures with two magnitude levels where size is an additional descriptor

Differentiation of size-based gestures is easier than angle-based gestures and offers higher confidence during input. Size-based gestures also need less continuous attention, have reduced risk of potential error while bending the device, and are associated with less variability and fewer false large magnitude levels. Considering these factors, we recommend the use of only size-based gestures with two magnitude levels in the same context where the size of bend is the additional descriptor along with the basic descriptors (location and direction). Even in a situation where two magnitude levels of size-based gestures are not used, which reduces the potential drawback of ambiguity in the presence of angle-based gestures, we recommend avoiding the frequent use of the large magnitude level of angle. The reason is the increased effort in large angles, which may further increase with reduced device flexibility and also create occlusion for sighted users.

When calculated irrespective of location-direction pairs (Figure 4.8a), the confidence intervals of BLV and sighted user groups have smaller differences (less than 10 mm) for each magnitude level of size. In addition, the confidence intervals of the BLV group are lower than the sighted group for both small and large magnitude levels of size-based gestures. Considering both BLV and sighted user groups, we recommend using the ranges between the lower bounds of the BLV group and upper bounds of the sighted group corresponding to small (23.1 mm to 24.5 mm) and large (36.4 mm to 40.4 mm) magnitude levels of size. Accordingly, tactile markers or other means of affordances can be implemented for ease of identification and differentiation of two magnitude levels of size-based gestures.

4.1.5.2 Use of two magnitude levels of size at all corners (preferably top)

Considering the preference and performance of BLV and sighted participants, we recommend using two magnitude levels of size-based gestures at all four corner locations. Considering both BLV and sighted user groups, the ranges for small (23.1 mm to 24.5 mm) and large (36.4 mm to 40.4 mm) magnitude levels of size can be used for the corners. Since differentiation of two magnitude levels is found to be easier at top corners, out of four corners, top corners should get higher preference and should be mapped to frequently used functions.

4.1.5.3 Use of one magnitude level of size for both sides (preferably top)

Size-based gestures at the top and bottom sides (in portrait orientation) are commonly associated with increased variability, false large magnitude levels, difficulty in performing, and required effort. Although BLV participants preferred two magnitude levels of size, considering their performance and the sighted group's performance and preference, we recommend that preference should be given to the use of only one magnitude level of size-based gesture, that is, the large magnitude level, at the top and bottom sides. For this scenario, the range for the large magnitude level (36.4 mm to 40.4 mm) can be used considering both BLV and sighted user groups. However, including two magnitude levels of size requires a flexible device that allows ease of identification of bend lines and ease of performing both magnitude levels of size-based gestures on the sides. Since differentiation of two magnitude levels is found to be easier at the top side, the top side should get a higher preference and should be mapped to frequently used functions.

4.1.5.4 Use of both directions of bend for BLV users

Considering the preference and performance of BLV participants, we recommend using both directions of bend (upward and downward) while designing for BLV users. Although sighted participants can perform downward bend gestures and differentiate two magnitude levels towards the downward directions. Considering the sighted participants' preference and reported difficulties in performing downward bend gestures, we recommend that while designing for sighted users, the upward direction should get a higher preference and should be mapped to frequently used functions.

4.1.5.5 Use of the small magnitude level of angle in implementing a threshold-based strategy to provide discrete input

Considering the performance of both BLV and sighted groups and the preference of the sighted group, only size-based gestures should be used as an additional descriptor of bend gestures instead of angle-based gestures with two magnitude levels. However, every bend gesture performed on a flexible device generates an angle of bend. This default angle of bend associated with any bend gesture can be used to indicate the completion of the gesture to provide discrete input. For this purpose, an appropriate threshold needs to be decided. While

designing for both BLV and sighted groups, a decided threshold should be suitable for both user groups. Since the BLV group can easily perceive the change in angle of bend through tactile and kinesthetic sense and both groups can easily perform the small magnitude level of angle-based gestures, we recommend using this small magnitude level of angle for threshold-based gesture completion strategies. Furthermore, the BLV group's lower bound of the confidence interval for the small magnitude level of angle and the sighted group's upper bound of the confidence interval for the small magnitude level of angle are the same (64.6 degrees in Figure 4.8b). Therefore we recommend using this value (approximately 65 degrees) as a threshold to provide discrete input. However, it is necessary that the gesture completion is accompanied by a user group-appropriate feedback. While this small magnitude level of angle as a threshold is suitable for frequently used actions, for rarely used critical actions, performing a large angle-based gesture with conscious effort can be utilized as a threshold provided both magnitude levels are not used in the same context accompanied by only threshold-based gesture completion strategy.

4.1.5.6 Use of the large magnitude level of angle as the extreme angle required for continuous input

Performing a bend gesture results in a continuous change in the angle of bend. This continuous change in angle can be used to provide continuous input to modify a parameter value (for instance, volume and brightness) where the maximum value of the parameter needs to be mapped with an extreme angle of a comfortable bend gesture. While designing for both BLV and sighted groups, performing the common extreme angle should be comfortable for both user groups. In addition, both groups should be able to perceive small changes in angle to control the parameter value. However, we found that, unlike all BLV participants, sighted participants who depend only on visual perception can not easily perceive the small changes in angle. To address this issue, having a large angle mapped to the maximum parameter value will allow the sighted group to easily map the changes in angle to the changes in the parameter value. On the other hand, bend gestures with very large angles of bend suffer from occlusion due to the device's bent surface. Considering these factors, for continuous input, we recommend using the upper bound of the confidence interval for the large magnitude level of angle by the BLV group (91.7 degrees in Figure 4.8b) as the extreme

angle to map with the maximum value of the parameter. However, every change in the parameter value must be accompanied by a user group-appropriate feedback.

4.2 Study on Bend Gesture Completion Strategies

In the previous study (reported in Section 4.1), we investigated user performance and preference for two additional descriptors of bend gestures, which are size and angle, in addition to the basic descriptors (location and direction). This study aims to identify user-preferred bend gesture completion strategies for providing discrete and continuous input. We involved both BLV and sighted users in this study to draw more informed, accessible and inclusive design decisions. However, this thesis's contributions focus on the BLV user group's preferences. Accordingly, the findings and observations concerning only the BLV user group are taken forward for the subsequent studies. The findings of this study answer the third research question "RQ 3: What are the preferred bend gesture completion strategies of the BLV user group to provide discrete and continuous input to reduce unwanted or unintended input?" (RQ 3 reported in Section 1.2).

The act of performing bend gestures on a flexible device (Figure 4.10) is dynamic in nature. Usually, a dynamic gesture involves three stages: start, update, and end stages (Ramamoorthy, Vaswani, Chaudhury, & Banerjee, 2003). For bend gestures, the initial neutral or relaxed state (Figure 4.10a) before bending the device is commonly the start stage (Schwesig et al., 2004; Kildal, 2012), and the gradual bending is the update stage. For continuous input, this gradual bend is detected by the system, and respectively the output parameter value changes until the end stage indicates the gesture's completion to confirm a value. For discrete input, the end stage is detected by the system, and accordingly, the discrete output action is triggered. Although the end stage plays a vital role in completing the gestures, based on our understanding, the existing research provides evidence of implementing gesture completion strategies that depend on reaching or crossing predefined thresholds (On-crossing a Threshold strategy) to provide discrete input (Daliri & Girouard, 2016; Schwesig et al., 2004; J. I. Watanabe et al., 2008; Tajika, Yonezawa, & Mitsunaga, 2008; Wightman et al., 2011; Kildal, 2012; Girouard et al., 2015; Kildal & Boberg, 2013; Lo & Girouard, 2017) and releasing the bend (On-release strategy) to confirm continuous input (Schwesig et al., 2004; Kildal, 2012). The major drawback of using only a threshold-based strategy in its simplest form is the lack of freedom to reject unwanted or unintended input, as reaching or crossing the threshold triggers the output action immediately. For confirming continuous input, the simplest form of gesture completion on releasing the bend also has

similar drawbacks. As soon as the bend is released (or starts to move back), the respective value for the most recent degree of bend gets confirmed for the output parameter. As a result, only uni-directional (either increase or decrease) manipulation of the output parameter is allowed before confirming a value. Therefore, with these two strategies, rejecting unwanted or unintended input becomes a challenge during bend gesture-based interaction. We conducted this study on a smartphone-sized flexible mock-up prototype to identify user-preferred bend gesture completion strategies for discrete and continuous input and to understand their potential to reduce unwanted or unintended input. In this study, we identified four strategies for discrete input and three strategies for continuous input.

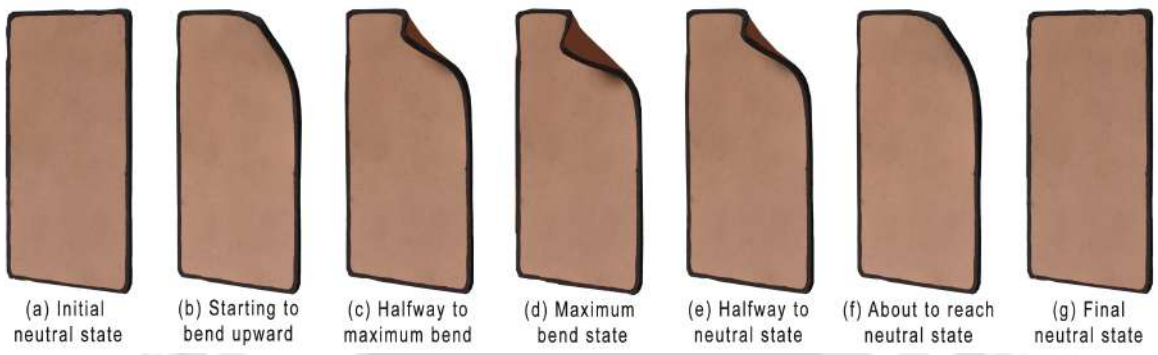


Figure 4.10: Different intermediate states while bending a flexible device.

4.2.1 Methodology

4.2.1.1 Participants

For BLV participants, we contacted an academic institute requesting students' voluntary participation. Participation criteria were: the percentage of visual impairment (*Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018) should be 70% or more according to their medical certificates, no upper limb disorder, and a minimum of 3 years of experience using smartphones through screen reader (Google TalkBack). As shown in Table 4.7, ten BLV students (8 male and 2 female) with a percentage of visual impairment 100% (except one has 80%) between the ages of 18-22 years (Mean = 19.4, SD = 1.58) participated in the study. For the sighted group, we asked first-year university students for their voluntary participation. The participation criteria were: minimum 3 years of experience using smartphones and no upper limb disorder. Fifteen sighted students (9 male and 6 female) between the ages of 18-25 years (Mean = 20.73, SD = 2.49) participated in the study. There

were three left-handed participants. We have taken prior consent from all participants and followed the ethics of conducting research on human subjects.

Table 4.7: Demographic information of BLV participants.

Participant	Age	Gender	Handedness	Visual impairment (%)	Impairment since	Perception of light
P1	18	M	Right	100	4 years old	Yes
P2	19	M	Right	100	Birth	No
P3	20	M	Right	100	19 years old	Yes
P4	18	M	Left	100	9 years old	Yes
P5	20	M	Left	100	Birth	Yes
P6	22	M	Right	100	Birth	Yes
P7	18	M	Right	80	11 years old	Yes
P8	18	F	Right	100	10 years old	Yes
P9	19	F	Right	100	Birth	Yes
P10	22	M	Left	100	Birth	Yes

4.2.1.2 Apparatus

We conducted the study with a smartphone-sized flexible silicone-cast mock-up prototype (154 mm x 74 mm x 6 mm) measuring 6.7 inches at the diagonal (Figure 4.11a). As shown in Figure 4.11b, the prototype comprises a flexible 3D-printed internal structure (thickness 1mm, shore hardness 95A) sandwiched between two silicone layers of shore hardness 25A for higher flexibility (Kildal, 2012; Kildal & Wilson, 2012).

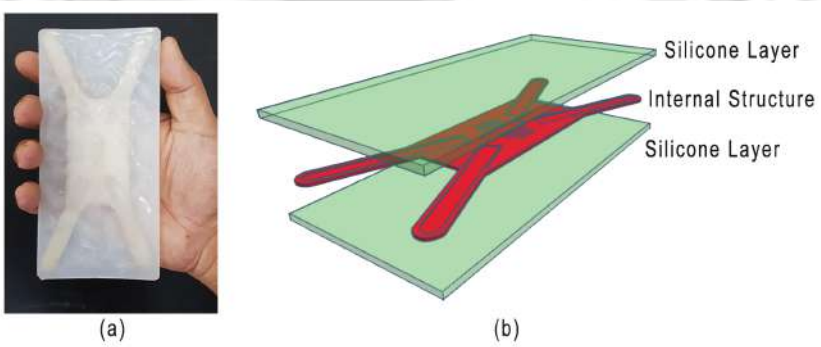


Figure 4.11: (a) The smartphone-sized mock-up prototype and (b) the prototype contains a flexible 3D-printed internal structure sandwiched between two silicone layers.

4.2.1.3 Task

We asked the participants to assume interacting with a flexible smartphone in two scenarios and propose bend gesture completion strategies to confirm discrete and continuous inputs. We selected the following scenarios, which are familiar to users, distinguishable as discrete and continuous inputs, and also been studied with bend gestures (Ahmaniemi et al., 2014; Lahey et al., 2011; Schwesig et al., 2004). To reduce the effort in learning and performing bend gestures, we selected only the corners and asked them to perform bend gestures towards upward and downward directions. No external feedback was provided as the gestures' ends (completions) were proposed by the participants.

Scenario-1: This scenario was to provide discrete input to open a file or application. We asked the participant to assume that a selected file or application will open as soon as the participant indicates the completion of the bend gesture.

Scenario-2: This scenario was to provide continuous input to change the volume. We asked the participant to assume that the volume changes with respect to the degree of bend and the current value will be confirmed for the volume parameter as soon as the participant indicates the completion of the gesture.

4.2.1.4 Procedure

We conducted the study in a controlled environment. Before conducting the study, we organized two separate training sessions (one week before and immediately preceding the study) to help the participants effectively familiarize themselves with bend gestures to utilize the full potential of the device's flexibility and to reduce the effect of prior experience (Morris et al., 2014). In the first training session, we demonstrated (by holding BLV participants' hands) the bend gestures at the corners, while one hand was holding the device and another hand was bending the corners towards upward and downward directions. Then the participants practiced the gestures under the moderator's observation and assistance (if required) until they found themselves ready. We followed the same procedure for the second training session before introducing the participants to the concept of gesture completion strategy. Irrespective of participants' prior knowledge, we explained the need and role of gesture completion strategies for discrete and continuous inputs by referring to the scenarios. We introduced them to the threshold-based strategy for discrete input and releasing the bend

gesture for continuous input and explained their drawbacks. This was done to help the participants propose new strategies that can overcome the drawbacks.

We referred to each gesture by combining the names of the bent location (corner) and direction as a pair (Borah & Sorathia, 2019b) for example, "Top-Right-Corner Bend-Upward". First, we asked the participants to perform bend gestures at one corner (for both directions) to provide discrete input (Scenario-1). Then we asked the participants to explore a set of gesture completion strategies that are intuitive (Borah & Sorathia, 2019b; Byrd, 2014; Grandhi, Joue, & Mittelberg, 2011), easy to perform, and do not involve other input modalities such as touch or voice. The exact process was repeated for the remaining corners, where we asked the participants to perform the previously explored strategies and explore new strategies. Then participants performed the final set of strategies for each location and direction. They finally proposed a sequence of preferences (maximum three) that are intuitive, easy to perform, and can overcome the drawbacks of existing strategies. After they proposed the strategies, we asked them to share their experience regarding confidence during input, the scope for one-handed interaction, and potential application. Then we repeated this process for continuous input (Scenario-2). We randomized the sequence of scenarios and corners for each participant.

4.2.2 Results and discussion

The BLV and sighted participant groups proposed a total of 42 strategies (26 for discrete and 16 for continuous inputs) and 75 strategies (44 for discrete and 31 for continuous inputs), respectively. The demonstrations and the verbal descriptions of the strategies enabled us to identify the functionally similar strategies. Finally, as presented in Table 4.8, we identified four unique strategies (D1, D2, D3, and D4) for discrete input and three unique strategies (C1, C2, and C3) for continuous input. We calculated the total number of participants from both BLV and sighted groups who reported the strategies as their first, second, and third preferences and presented in Table 4.8 as the sum of the two groups. For instance, the structure followed to present this information in Table 4.8 is as follows: Number of BLV participants + Number of sighted participants = Total number of participants. These preferences are based on the participant's perceived intuitiveness, ease of performance, and ability to overcome the drawbacks of existing strategies. The majority of the BLV

participants reported the On-Hold strategies (D1 and C1) as their first preferences for discrete (80%) and continuous (88.89%) inputs. The majority of the sighted participants reported the On-Release strategy (D2) and the On-Hold strategy (C1) as their first preferences for discrete (76.92%) and continuous (66.67%) inputs, respectively.

Table 4.8: The unique strategies proposed by BLV and sighted participants.

Strategy codes	Strategy names	Input types	Preferences of (BLV + Sighted = Total) participants			Total Count out of 25 (10+15)
			First preference	Second preference	Third preference	
D1	On-Hold	Discrete	8+2=10	1+10=11	1+2=3	10+14=24
D2	On-Release	Discrete	2+10=12	3+2=5	0+1=1	5+13=18
D3	On-Relax	Discrete	0+2=2	1+1=2	4+6=10	5+9=14
D4	On-Double-Bend	Discrete	0+1=1	5+2=7	1+5=6	6+8=14
C1	On-Hold	Continuous	8+10=18	1+4=5	0+1=1	9+15=24
C2	On-Second-Bend	Continuous	2+3=5	4+2=6	0+2=2	6+7=13
C3	On-Quick-Relax	Continuous	0+2=2	0+6=6	1+1=2	1+9=10

During the analysis of participants' verbal feedback, we noticed that confidence during input was a major deciding factor for the BLV user group. While performing the bend gestures, the grip on the bent location allowed the BLV participants to perceive the innate tactile and kinesthetic feedback of bend gestures. Since they solely relied on tactile and kinesthetic perception (in the absence of other feedback modalities), their preferences were inclined towards strategies (D1, D4, C1, and C2) that not only allowed them to continue the grip on the device, but also offer rejection mechanisms.

In contrast, the ease of performing the strategies was often a major deciding factor for the sighted participants during discrete input. However, during continuous input, confidence during input was a major deciding factor due to the difficulty in measuring the degree of bend only through visual perception. While performing the bend gestures, the continuous grip on the bent location offered them higher confidence.

We also noticed that both participant groups often referred to their prior experience with button and touch-based interactions, which is similar to the observations reported in the existing literature (Trewin, Swart, & Pettick, 2013; Kane, Bigham, & Wobbrock, 2008;

Potter, Weldon, & Shneiderman, 1988). Considering legacy-inspired interactions to be easily guessable and learnable (Wobbrock et al., 2005; Morris et al., 2014), we believe these strategies can help touchscreen users easily adapt to bend gestures of flexible devices.

We also noticed participants' inconsistency in performing degrees of bend, especially a few participants who performed very small degrees of bend for discrete inputs. Implementing such small bend angles for discrete input may contribute to the increase in unintended inputs, hence leading to poor user experience. We believe using a bend angle-based activation threshold (Lo & Girouard, 2017) in combination with the proposed strategies can address this issue. Crossing this activation threshold does not trigger actions; rather confirms the current bend as a valid bend and informs the user to go ahead with the proposed strategies.

4.2.2.1 Gesture completion strategies for discrete input

4.2.2.1.1 Gesture completion On-Hold (D1):

This strategy indicates the bend gesture's completion on holding the bend in the same state (without any change in the degree of bend) for a predefined interval of time (hold-time). As soon as the predefined interval ends, the associated action gets triggered. As a result, this strategy offers the freedom to reject unwanted or unintended input by avoiding the hold-time. However, this hold-time does not allow quick input. Although the hold-time between 1 - 1.5 Sec was preferred by the majority of the BLV (70%) and sighted (64%) participants, further investigation is required to identify one or multiple appropriate values. According to both participant groups, this strategy can be applied during one-handed interaction. The higher confidence during input reported by the BLV participants resulted in maximum BLV participants under the first preference (D1 row in Table 4.8). In contrast, the associated hold-time resulted in maximum sighted participants under the second preference. One BLV participant said, "When I bend, I can feel the device all the time, I will not hold this bend unless I am confident about the action". Literature (Trewin et al., 2013) also discussed a similar touch input strategy of Android devices.

4.2.2.1.2 Gesture completion On-Release (D2):

This strategy indicates the completion of a bend gesture on releasing the bend. As soon as the bend is released (or starts to move back), the associated action gets triggered. As a result, it

allows the user to decide the precise moment of discrete input. However, this strategy alone does not offer the freedom to reject unwanted or unintended input. According to both participant groups, this strategy can be applied during one-handed interaction. The ease of performing the strategy and its intuitiveness resulted in maximum sighted participants under the first preference (D2 row in Table 4.8). In contrast, the reduced confidence during input reported by the BLV participants and the lack of rejection mechanism resulted in a lower (less than or equal to 50%) number of proposals by this group. One sighted participant mentioned, "It is easier than threshold-based strategy in terms of reduced cognitive load as I don't have to focus on bending the device to trigger an action". Literature also reported similar strategies for touch (Potter et al., 1988) and bend gesture-based (Gallant et al., 2008) input.

4.2.2.1.3 Gesture completion On-Relax (D3):

This strategy indicates the bend gesture's completion on reaching the final neutral state (Figure 4.10g) after releasing the bend. As soon as the bent location reaches the final relaxed or neutral state, the associated action gets triggered. Although this strategy alone does not offer the freedom to reject unwanted or unintended input, according to the participants, bending the device in the opposite direction (without stopping at the neutral state) can serve the purpose. However, they also reported that the application of this strategy would be difficult during one-handed interaction due to the rejection mechanism. The less intuitive rejection mechanism at the cost of more effort resulted in maximum sighted participants under the third preference (D3 row in Table 4.8). In contrast, the reduced confidence during input reported by the BLV participants and the less intuitive rejection mechanism resulted in a lower (less than or equal to 50%) number of proposals by this group. A similar strategy was reported in the literature (Kildal et al., 2012) to provide bend gesture-based input during bi-manual interaction.

4.2.2.1.4 Gesture completion On-Double-Bend (D4):

This strategy indicates the bend gesture's completion on quickly performing double (two identical) bend gestures with the same location and direction. After performing the first bend gesture, the user quickly starts the second bend gesture, and as soon as the second bend gesture reaches the previous gesture's maximum degree of bend, the associated action gets triggered. As a result, this strategy offers the freedom to reject unwanted or unintended input by avoiding repeated bend gestures. According to both participant groups, this strategy can

be applied during one-handed interaction. The higher confidence during input at the cost of more effort reported by the BLV participants resulted in maximum BLV participants under the second preference (D4 row in Table 4.8). In contrast, the additional effort required to perform repeated bend gestures resulted in maximum sighted participants under the third preference. Kane et al., 2008 reported a similar strategy for touch-based input interaction.

4.2.2.2 Gesture completion strategies for continuous input

For continuous input, a user starts a bend gesture, and based on the degree of bend, the output parameter value increases or decreases. This manipulation of the parameter is temporary until the user confirms a respective value for a degree of bend by indicating the gesture's completion at that degree of bend.

4.2.2.2.1 Gesture completion On-Hold (C1):

This strategy indicates the bend gesture's completion on holding the bend in the same state (without any change in the degree of bend) for a predefined interval of time (hold-time). As soon as the predefined interval ends, the respective value for the degree of bend gets confirmed. As a result, this strategy allows the rejection of unwanted or unintended input and bi-directional manipulation of the output parameter before confirming a final value. However, this hold-time does not allow quick input. Since, unlike discrete input, a user has to try the manipulated value before confirming it, the majority of the BLV (78%) and sighted (60%) participants preferred a higher hold-time between 1.5 - 2 Sec. According to the participants, this strategy can be applied during one-handed interaction. The higher confidence during input reported by both groups and the ability to overcome the drawbacks resulted in maximum participants under the first preference (C1 row in Table 4.8).

4.2.2.2.2 Gesture completion On-Second-Bend (C2):

This strategy indicates the currently performing bend gesture's completion on performing a second bend gesture at a different location. When a user is manipulating the output parameter by performing a bend gesture, as soon as the user decides to confirm the respective value for a degree of bend, the user performs a second bend gesture at a different location to confirm the value. As a result, this strategy allows the rejection of unwanted or unintended input, the

user-decided precise moment of input, and bi-directional manipulation of the output parameter before confirming a final value. Bi-manual interaction is required for this strategy. Despite the higher confidence during input reported by both participant groups, the bi-manual interaction and associated effort resulted in maximum BLV participants under the second preference and the lack of intuitiveness resulted in a lower (less than or equal to 50%) number of proposals by the sighted group (C2 row in Table 4.8). Kane et al., 2008 reported a similar touch input strategy (Second-Finger Tap) for BLV users.

4.2.2.2.3 Gesture completion On-Quick-Relax (C3):

This strategy indicates the completion of the bend gesture on reaching the final neutral or relaxed state (Figure 4.10g) quickly. As soon as the user decides to confirm the respective value for a degree of bend, the user allows the bent location to quickly reach its final relaxed state (freely or manually) without any intermediate delay. Quickly reaching the neutral state acts as confirmation. As a result, this strategy allows bi-directional manipulation of the output parameter before confirming a final value. According to the participants, the rejection of unwanted or unintended input can be achieved by slowly moving the bent location back to its relaxed state, which could be difficult during one-handed interaction. We believe implementing this strategy will require sophisticated hardware support and pattern recognition algorithms. The less intuitive rejection mechanism with reduced confidence resulted in maximum sighted participants under the second preference (C3 row in Table 4.8). In contrast, the lack of intuitiveness and reduced confidence resulted in a lower (less than or equal to 50%) number of proposals by BLV participants.

4.2.3 Implications and recommendations

4.2.3.1 Gesture completion strategies for both BLV and sighted users

On-Hold (D1), On-Double-Bend (D4), On-Hold (C1), and On-Second-Bend (C2) strategies are the most appropriate while designing for both BLV and sighted users and eyes-free interaction by sighted users, as these strategies offer higher confidence during input.

4.2.3.2 Gesture completion strategies for quick input

On-Release (D2), On-Relax (D3), and On-Double-Bend (D4) strategies are appropriate for quick discrete input. While On-Release (D2) strategy is more suitable when a precise moment of input is demanded (for example, pause audio at a specific moment on the timeline). During continuous input, the On-Second-Bend (C2) strategy is more suitable for quick input during bi-manual interaction (for example, change volume and content zooming).

4.2.3.3 Gesture completion strategies for discrete input for critical actions

On-Hold (D1) and On-Double-Bend (D4) strategies are appropriate for critical actions, where triggering the action can lead to significant or irreversible changes in the outcome (for example, closing an application and deleting a file). On-Hold (D1) is also suitable for shortcuts and input without shaking the device (for example, starting the camera and capturing an image).

4.2.3.4 Multiple actions with the same bend gesture

Mapping multiple actions to the same bend gesture can reduce frequent re-gripping. This can be achieved by mapping different actions to different discrete input strategies of the same bend gesture. Multiple actions can also be mapped with different hold-times of On-Hold (D1) strategy and different degrees of bend of On-Release (D2) and On-Relax (D3) strategies. Also, two related actions can be mapped with the update-stage and end-stage of the same gesture.

4.3 Summary

This chapter reported the two studies of Phase II (Study 3 and Study 4). Considering the findings from the previous chapter (Study 1 reported in Section 3.1), which evidence that BLV students often take help from the sighted, we included both BLV and sighted users during the two studies of this Phase II (Study 3 and Study 4) reported in this chapter. However, the contributions of this thesis are focused on the BLV user group's performance and preferences. Accordingly, the findings and observations concerning only the BLV user group are taken forward for the subsequent studies. The first study reported in this chapter (Study 3 reported in Section 4.1) details the investigation of users' performance and preference for two magnitude

levels of size and angle of bend gestures as two additional descriptors of bend gestures on a smartphone-sized deformable prototype. The findings of this Study 3 answer the second research question (RQ 2 reported in Section 1.2). The second study reported in this chapter (Study 4 reported in Section 4.2) details the identification of user-preferred gesture completion strategies for discrete and continuous inputs. The findings of this Study 4 answer the third research question (RQ 3 reported in Section 1.2). In the next chapter (Chapter 5), we report the two studies of Phase III (Study 5 and Study 6). The first study reported in the next chapter (Study 5) details the participatory design of the bend gesture-based digital drawing tool named Naamya. The second study reported in the next chapter (Study 6) details the evaluation of Naamya compared to a pegboard-based drawing tool (Taylor Arithmetic Slate).

Chapter 5

Design and Evaluation of Naamya

The previous chapter (Chapter 4) presented two studies, including an investigation of users' performance and preference for two magnitude levels of size and angle of bend as two additional descriptors of bend gestures and identification of user-preferred gesture completion strategies for discrete and continuous inputs. This chapter reports the two studies of Phase III (Study 5 and Study 6) that answer the fourth and fifth research questions (RQ 4 and RQ 5 reported in Section 1.2). The first study reported in this chapter (Study 5) details the participatory design of the bend gesture-based digital drawing tool named Naamya. The second study reported in this chapter (Study 6) details the evaluation of Naamya compared to a pegboard-based drawing tool (Taylor Arithmetic Slate).

5.1 Participatory Design of Naamya

Participatory design is an approach to design that seeks to actively involve stakeholders in the design process in order to ensure that the outcome of the design process is usable and meets the user's needs (Schuler & Namioka, 1993; Muller & Kuhn, 1993; Abras, Maloney-Krichmar, & Preece, 2004). The participatory design provides an opportunity to support a user-centred approach to design (Abras et al., 2004). Research on inclusive and accessible design can utilise this method (Waller, 2021) to address the late involvement of people with disabilities during the product cycle or their limited participation in the design process (Oswal, 2014). We utilized this participatory approach to design the bend gesture-based drawing tool (Naamya) by involving students with visual impairment or blindness and their teachers in the

design process. This study comprises two phases. The first phase of this study aims to finalise the required feedback modalities of the bend gesture-based drawing tool. The second phase of this study aims to finalise the tool's basic and advanced functions. This phase also aims to map these functions with bend gestures and to finalise the bend gesture completion strategies to trigger associated functions. Together the findings of this study answer the fourth research question "RQ 4: How can the bend gestures be used to design a geometric shape drawing tool that corresponds to the user's existing mental model?" (RQ 4 reported in Section 1.2).

5.1.1 Methodology

5.1.1.1 Participants

We contacted two academic institutes requesting students' voluntary participation. Participation criteria for students were: their visual impairment (*Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018) should be 70% or more according to their medical certificates, no upper limb disorder, learned tactile drawing of primitive geometric shapes in the curriculum, and a minimum of three years of experience using smartphones through screen readers. Ten students (8 male and 2 female between the ages of 18-22 years, M=20.4, SD=1.65) participated in the study (S1 - S10 in Table 5.1). All the students have at least three years of experience using smartphones with Google TalkBack. We also requested the teachers for their voluntary participation. Participation criteria for teachers were: they should be either sighted or their visual impairment (*Guidelines for Assessment of Disabilities under RPwD Act. 2016 Notified*, 2018) should be 70% or more according to their medical certificates, and no upper limb disorder. The teachers must have a minimum of five years of experience teaching mathematics and/or operating digital devices (smartphones and computers) and be active smartphone users who employ screen readers. Four teachers (3 male and 1 female between the ages of 35-45 years, M=39.75, SD=4.57) participated in the study (T1 - T4 in Table 5.1). Three teachers were visually impaired (visual impairment 100% since birth), and one teacher is sighted. Two teachers (one visually impaired T1 and one sighted T4) have experience teaching geometry and computer skills to students with visual impairment or blindness. All the teachers have experience using smartphones and teaching students how to use smartphones using screen readers.

Table 5.1: Demographic information of student (S1-S10) and teacher (T1-T4) groups who participated during the participatory design.

Participant	Age	Gender	Handedness	Visual impairment (%)	Impairment since	Perception of light
S1	22	M	Right	100	Birth	No
S2	18	M	Right	100	Birth	Yes
S3	18	M	Right	100	Birth	Yes
S4	22	M	Right	100	Birth	Yes
S5	20	M	Right	80	11 years old	Yes
S6	22	M	Left	100	Birth	Yes
S7	21	M	Right	100	Birth	No
S8	20	F	Right	100	Birth	Yes
S9	22	F	Right	100	10 years old	Yes
S10	19	M	Left	100	9 years old	Yes
T1	37	M	Right	100	Birth	Yes
T2	35	M	Right	100	Birth	Yes
T3	45	F	Right	100	Birth	Yes
T4	42	M	Right	Sighted	-	-

5.1.1.2 Task

In the first phase, we asked the participants to examine the feedback modalities selected based on existing literature and share their opinions on finalising them for implementation of the bend gesture-based drawing tool.

In the second phase, we asked the participants to examine the basic and advanced functions (Table 5.2) and share their opinions on the need for modification and the scope for addition. Finally, we asked the participants to share their opinions on mapping these functions with bend gestures (Figure 5.1) and the bend gesture completion strategies to trigger associated functions. For this phase, we used the mock-up prototype and the silicone-cast smartphone-sized functional prototype with the previously finalised feedback modalities.

5.1.1.2.1 Initial set of functions of the drawing tool:

We identified several functions during the observational study reported in Chapter 3 that could be potentially helpful for designing a digital tool that corresponds to the user's mental model of

using existing pegboard-based drawing tools. We categorized these functions into three levels such as basic, advanced, and smart functions (reported in Table 3.3). For this participatory design study, we selected the basic and advanced functions (Table 5.2) for mapping with bend gestures. Later, for the evaluation of Naamya, we implemented the basic functions that are essential for drawing.

Table 5.2: Initial set of basic and advanced functions and their descriptions.

Function	Level	Description
Navigate FOCUS	Basic	Move FOCUS from one hole to another towards one of the eight directions.
Insert Peg	Basic	Insert a peg in the current hole in FOCUS.
Remove Peg	Basic	Remove the peg (if it exists) from the current hole in FOCUS.
Open Menu	Advanced	Open the vertical menu.
Close Menu	Advanced	Close the vertical menu if it is already open.
Navigate a List	Advanced	Vertically navigate a list of items towards the top or bottom.
Confirm	Advanced	Confirm the currently selected menu item or trigger YES.
Cancel or Reject	Advanced	Go back after cancelling the menu item selection process or trigger NO.
New Board	Advanced	Create a new empty virtual pegboard.
Open Board	Advanced	Populate a list of previously created boards.
Rename Board	Advanced	Rename the currently open virtual pegboard.
Save As	Advanced	Save the currently open virtual pegboard as a vector image.
UNDO	Advanced	Erase the last change done on the virtual pegboard.
REDO	Advanced	Restore the change that was undone.
Label a Grid Position	Advanced	Add an audio label to the current grid position (empty or filled) in FOCUS.
Clear All Pegs	Advanced	Remove all pegs and move FOCUS to Row 1 and Column 1.
Help	Advanced	Open a user guide.
Exit	Advanced	Exit from the drawing application.

5.1.1.2.2 Initial set of bend gestures:

We selected bend gestures with three descriptors of bend (location, direction, and size) as identified during the literature review reported in Section 2.3 and investigated in Section 4.1 of Chapter 4. Twenty-eight bend gestures (Figure 5.1) with eight bend gesture locations (4 Corners, Top and Bottom Sides, and horizontal and vertical axis of symmetry), two directions of bend (Bend-upward and Bend-Downward), and two magnitude levels of the size of bend (Small-size and Large-size) were selected for the training session. Although the participants were trained with these twenty-eight simple bend gestures (Figure 5.1), they were informed that they could also perform and select compound gestures.

Figure 5.1: Initial set of twenty-eight simple bend gestures.

5.1.1.2.3 Bend gesture completion strategies:

The bend gesture completion strategies selected for this participatory design study include both existing and newly explored (Section 4.2) strategies. These selected gesture completion strategies are On-Crossing a Threshold, On-Hold, On-Release, On-Relax, and On-Double Bend for discrete input and On-Release, On-Hold, On-Second-Bend, and On-Quick-Relax for continuous input. With the evidence from existing literature (Whitaker, 2020; McLaughlin, 2019) and our understanding from the study on bend gesture completion strategies (reported in Section 4.2), we used three types of hold-time or hold delays (short, medium, and long) for the On-Hold gesture completion strategy. Accordingly, we implemented a short hold-time of 0.5 Sec (Short On-Hold strategy), a medium hold-time of 1.5 Sec (Medium On-Hold strategy), and a long hold-time of 3 Sec (Long On-Hold strategy) in the functional prototype.

5.1.1.3 Apparatus

We used two smartphone-sized flexible prototypes for this study. A mock-up prototype (Figure 5.2) was used during the training session and the second phase of the study. A functional silicone cast prototype (Figure 5.3) was used during the training session and both phases of the study. We followed a grid-based drawing process as it corresponds to the mental model of drawing on pegboards as identified in Chapter 3 and reported in the literature (Kurze, 1996; Kamel & Landay, 1999; Struiksma, Noordzij, & Postma, 2009; Szubielska, 2014; Fernando & Ohene-Djan, 2021).

Figure 5.2: Mock-up prototype made of EVA foam with 32 (8x4) dots on the top surface. (a) The user points to the dot at Row 1 and Column 1 (top-left corner hole) and mentions that this dot or imaginary hole is currently in FOCUS. (b) The user performs a bend gesture to move the FOCUS towards the right by one step. (c) After performing the gesture, the user points to the dot at Row 1 and Column 2 and mentions that the FOCUS is shifted to this dot.

5.1.1.3.1 Mock-up prototype:

We developed the mock-up prototype with EVA foam with 32 (8 rows and 4 columns) embossed circular dots (also made of EVA foam) on the top surface (Figure 5.2). We used these 32 embossed dots to refer to digital holes. We used this mock-up prototype for ease of understanding and explanation while the final prototype does not contain such tactile dots.

5.1.1.3.2 Functional Prototype:

We fabricated the functional smartphone-sized prototype (Figure 5.3c) where a flexible 3D-printed internal structure (Figure 5.3a) was embedded inside the silicone cast prototype. The prototype measures 6.7 inches (170 mm) at the diagonal and the dimension of the prototype (154 mm x 74 mm x 7 mm) was decided to match the size of commonly used smartphones. In the previous study on size-based gestures reported in Chapter 4, we found that the participants shared their preference for tactile markers on the device surface that enable them to differentiate size-based gestures and perform bend gestures easily. To address this, we added grooves on the device surface considering its positive effect reported in the literature (Ernst et al., 2017). We used 2 mm wide triangular grooves or V-grooves (Ebefors, Kälvesten, & Stemme, 1998) with 1 mm depth along the bend lines (Figure 5.3b) that can allow users to bend the device with reduced effort without crowding the prototype's surface with multiple grooves of higher widths. Findings from Chapter 4 helped us to make necessary design decisions regarding the position of the bend lines. As shown in Figure 5.3b, for two magnitude levels of size-based bend gestures, two grooves were placed at each corner and the top and bottom sides of the prototype on both upper and lower surfaces.

In addition, we decided to fabricate the silicone cast prototype with higher flexibility along the bend lines that could enable users to perform bend gestures with reduced effort. The 3D-printed internal structure's design (size and shape) can produce varying-rigidity zones on a silicone cast prototype without changing the overall thickness of the prototype (Borah & Sorathia, 2022). We took this opportunity to offer higher flexibility along the bend lines (Figure 5.3b), including the horizontal and vertical axes of symmetry. We achieved this by reducing the thickness of the internal structure along the bend lines as shown in Figure 5.3a. The minimum thickness of 0.2 mm of the 3D-printed internal structure is maintained along the bend lines, and the rest is of a maximum thickness of 2mm. This is further modified by

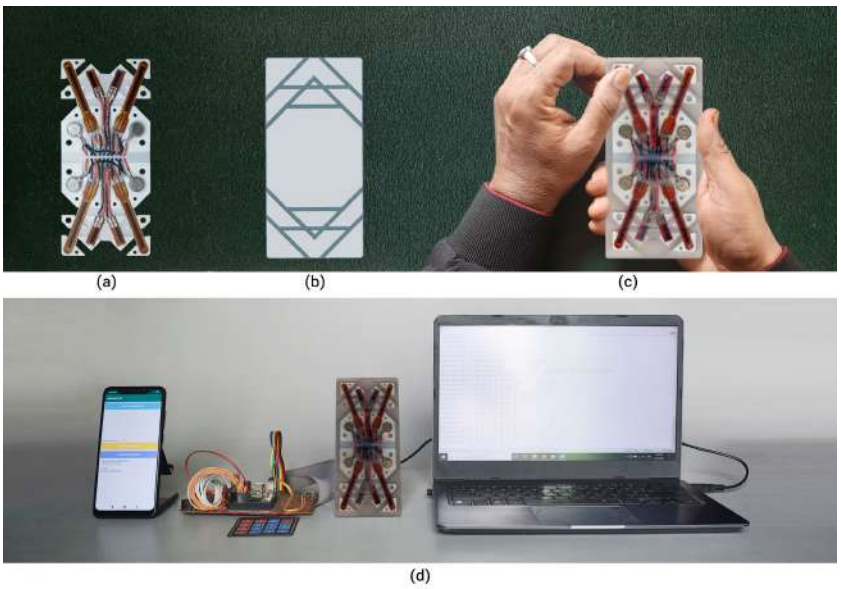


Figure 5.3: (a) 3D-printed internal structure equipped with sensors and vibration motors. (b) Grooves on the surface of the silicone cast. (c) Silicone cast smartphone-sized prototype. (d) The final functional setup containing the silicone cast prototype connected to Arduino. Audio description is provided using the Android smartphone's Text to Speech engine. The serial port monitor displays the progress of the drawing.

removing the thin segments along the bend lines, except for those required for holding the sensors. This resulted in a minimum thickness of 0.0 mm (area without 3D-print) and a maximum thickness of 2 mm. This offered varying-rigidity zones on the final silicone-cast prototype without changing the overall thickness of the prototype. This also resulted in higher flexibility along the bend lines of the final silicone-cast prototype to offer ease of performing bend gestures.

As shown in Figure 5.3a, the 3D-printed internal structure is designed to hold four 2 inches long bi-directional and four 1 inch long uni-directional bend sensors and four coin-type flat, micro-vibration motors along with the connecting wires. We used four bi-directional bend sensors at the corners to detect the degree of bend towards both upward and downward directions. The uni-directional bend sensors were used to recognize the difference between small and large magnitude levels of bend gestures. Since the degree of bend is measured using 2 inches long bend sensors, the remaining 1 inch long bend sensors were sufficient to recognize the difference between small and large size-based gestures towards both upward

and downward directions. As shown in Figure 5.3a, we placed all the sensors and motors on the internal structure and sealed it with hot-melt adhesive. This also helped us avoid any potential damage to the motors that could be caused during silicone casting. We intentionally kept twelve small and eight large holes on the internal structure (Figure 5.3a) to allow the top and bottom silicone layers to attach to each other by keeping the internal structure in position.

We followed a similar fabrication process as reported in Section 4.1 which aligns with the existing literature (Borah & Sorathia, 2022) except for using a new mold to produce the grooves on both surfaces of the prototype (Figure 5.4a). This new mold contains a bottom mold and a mold cover to produce the grooves on both surfaces of the prototype. The casting process was completed in four steps - pouring the initial layer of silicone in the bottom mold, placing the internal structure, pouring the second layer of silicone, and finally, placing the mold cover on the top. We kept several holes on the mold cover to release the extra silicone out of the entire mold without pushing or disturbing the position and orientation of the internal structure (Figure 5.4b). After completing the fabrication, we tested the functional prototype's (Figure 5.3d) sensors and vibration motors and found them to be functioning correctly.

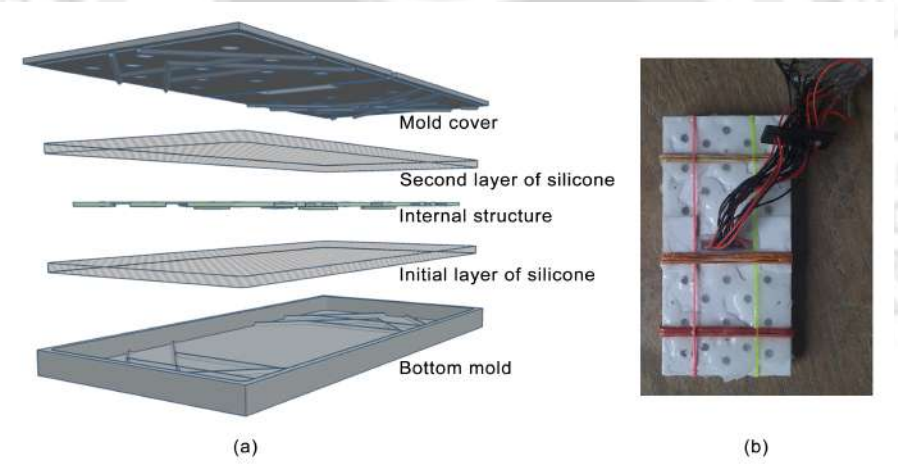


Figure 5.4: (a) The flexible 3D-printed internal structure sandwiched between two silicone layers. (b) Fabrication of the silicone cast functional prototype.

The sensors and actuators of the prototype were connected to an Arduino Mega 2560 microcontroller board. We selected Arduino Mega 2560 to take advantage of more memory and a higher number of Digital and Analog pins to connect multiple bend sensors. We used the open-source integrated development environment (IDE) of Arduino for writing the code and uploading it to the Arduino board. As shown in Figure 5.3d, the Arduino Mega 2560

microcontroller board is also connected to an Android smartphone via Bluetooth to produce audio descriptions utilizing the Text to Speech (TTS) engine of the Android operating system. The functional prototype is also equipped with a 4x4 matrix membrane-type keypad to provide input to the system without performing bend gestures. This keypad-based input was majorly utilized during training sessions to produce feedback without performing bend gestures. The prototype was also connected to a computer through a wire in order to display the progress of the drawing to the moderator via the serial port monitor of the IDE for Arduino. As shown in Figure 5.3d, the entire setup contains a smartphone, an Arduino Mega 2560 microcontroller connected to the circuit board, a 4x4 matrix membrane-type keypad, the silicone cast smartphone-sized prototype and a computer.

At first, we calibrated the bend sensors to detect approximately 30 and 65 degrees of bend angles for performing bend gestures. As reported in Chapter 4, 30 degrees is the activation threshold and 65 degrees is the trigger threshold for threshold-based gesture completion strategy (On-Crossing a Threshold). It indicates that an activation threshold of approximately 30 degrees (Lo & Girouard, 2017) for both upward and downward directions needs to be crossed while performing any bend gesture to consider it as a valid bend. Similarly, for the threshold-based gesture completion strategy, the user needs to bend approximately 65 degrees or more to indicate the completion of the gesture to trigger the associated function.

One of the primary feedback modalities selected for this tool is the audio description, that is, verbal description delivered via an audio channel. Providing an audio description that follows each function triggered in the application is a crucial part of the drawing tool to make it usable and more inclusive (Salway, 2007; Perego, 2018; Holland, 2009). Such concurrent audio-based feedback providing information regarding the progress in drawing also satisfies the first usability heuristic, "Visibility of System Status" proposed by Nielsen, 2020. As both haptic and auditory feedback are valuable in user perception (Toennies, Burgner, Withrow, & Webster, 2011), we also selected on-device vibrotactile feedback and non-verbal audio feedback (beep sound) to indicate a valid input provided to the bend gesture-based drawing tool. We placed four vibration motors at the center of the device oriented towards the corners in direct physical contact with the 3D-printed internal structure of the prototype (as shown in Figure 5.3a) to offer uniform vibrotactile feedback across the device. To offer a subtle experience through vibrotactile feedback, the sensitivity of the vibration motors was set to Pulse Width Modulation

(PWM) Wave equal to 100 (Caporusso et al., 2017). The non-verbal audio feedback (beep sound) was set to 1000Hz (Shoval, Borenstein, & Koren, 1998; Chen & Yeh, 2008). As the audio description immediately follows each function triggered, the duration for the vibrotactile feedback and the non-verbal audio feedback (beep sound) was set to 100 Milliseconds. We used this functional silicone cast prototype during the training session and both phases of this study. However, before using this prototype in the second phase, we finalised and implemented the feedback modalities in the first phase of this study.

5.1.1.4 Procedure

The study was conducted in a controlled classroom environment by dividing the participants into two groups. Each group contained five students and two teachers belonging to the same academic institution. We recorded the participants' verbal feedback and related critical observations while performing the assigned task for each phase. At first, the moderator informed the participants about the study's objectives. It is then followed by an explanation of the selected functions for the digital drawing tool, smartphone-sized flexible devices, bend gesture-based interaction and bend gesture completion strategies, regardless of their prior knowledge and experience with deformable devices. We provided a minimum of an hour-long uniform training session to each participant. For ease of explaining the functions of the drawing tool, we developed a non-functional mock-up prototype made of EVA foam with 32 (8 rows and 4 columns) embossed circular dots on the top surface (Figure 5.2). We asked the participants to assume these embossed dots as digital holes, which they could navigate from one hole to another and perform operations such as inserting or removing pegs. We used the functional prototype (Figure 5.3c) for practising the bend gestures and gesture completion strategies selected for this study. We introduced the participants to the available feedback modalities, such as audio description, non-verbal audio feedback (beep sound), and vibrotactile feedback. We also informed the participants that an activation threshold of approximately 30 degrees for both upward and downward directions needs to be crossed while performing any bend gesture to consider it as a valid bend. For the threshold-based gesture completion strategy, we asked the participants to bend approximately 65 degrees or more to indicate the completion of the gesture. For the On-Hold gesture completion strategy, we asked the participants to practice short, medium and long hold-time where the moderator

manually triggered the feedback by providing input through the 4x4 keypad. The moderator initially helped the participants to practice these gestures by holding their hands. Later, additional help was provided if and only if a participant made any mistakes in performing the gestures and gesture completion strategies. All the participants practised the gestures and gesture completion strategies multiple times until they reported themselves as ready to proceed. In addition to the simple bend gestures practised during the training session, we informed the participants that they could combine two simple bend gestures to perform compound bend gestures.

In the first phase, we asked the participants to examine the feedback modalities of the silicone-cast smartphone-sized functional prototype and share their opinions on finalising the feedback modalities for the bend gesture-based drawing tool. We used the functional prototype for this phase to experience the feedback modalities.

In the second phase, we asked the participants to examine the basic and advanced functions and finally map these functions with bend gestures and gesture completion strategies. We used both mock-up and functional prototypes for this phase. However, the feedback modalities finalised in the previous phase are implemented on the functional prototype before using it in this phase. For ease of understanding, we explained the functions in reference to the drawing process. We mentioned that at the very beginning, the hole at position Row 1 and Column 1 (top-left corner hole) would be set in FOCUS by default. A hole in FOCUS indicates that the outcome of user-performed actions will be reflected on that hole. The user can navigate this FOCUS from one hole to another hole and can perform an insert or remove peg operation at the current hole in FOCUS. We also mentioned that each progress in the drawing would be saved automatically after each input. After explaining the drawing process and the potential use of the selected functions, we asked the participants to share their opinions on the need for modification and the scope for addition to the selected functions. We asked the participants to use the functional prototype to rehearse the drawing process and requested them to share their opinions on mapping the functions with bend gestures. We informed the participants that they could use the mock-up prototype to explain their thoughts easily. Before finalising the mapping with bend gestures, we asked the participants to practise the potential mappings on the functional prototype with all the feedback. This also helped the participants to decide on the bend gesture completion strategies. We also informed the participants that a function could

be triggered by performing a bend gesture, by selecting it as a menu item, or by both means. We asked the participants to map easy and intuitive bend gestures and gesture completion strategies with the functions, primarily the frequently used functions.

5.1.2 Findings and discussion

The study comprises two phases. The first phase aims to finalise the required feedback modalities of the bend gesture-based drawing tool, and the second phase aims to finalise the tool's basic and advanced functions and their mappings with bend gestures and gesture completion strategies. The participants' verbal responses and related critical observations while performing the assigned task for each phase were transcribed and analysed using thematic analysis. The findings for each phase are reported in the following subsections.

5.1.2.1 Findings on feedback modalities

The objective of the first phase was to finalise feedback modalities. At first, for the audio description, we asked the participants regarding the need and the minimal structure of the audio description that is adequate and unambiguous (Manduchi & Coughlan, 2012; Hub, Diepstraten, & Ertl, 2003; Liu, Wang, Wang, & Qian, 2015). According to the majority of the participants, the audio description must follow the sequence "Triggered Function Name", "FOCUS Position in terms of Row Number and Column Number", and "Status as either Filled or Empty hole". For instance, when the user triggers the "Insert Peg" function at the grid position row number 1 and column number 1, which is an empty hole, the respective audio description is "Peg inserted, Row-1 Column-1 Filled". This structure of the audio description also reflects the third golden rule, "Offer Informative Feedback" proposed by Shneiderman et al., 2016. For instance, this structure answers the questions "Does the user know where they are in the process?" and "Does the user know what they have done after performing this action?" reported in the checklist (E. Wong, 2020) based on Ben Shneiderman's Eight Golden Rules (Shneiderman et al., 2016). All the participants found this structured audio description very helpful and compared it to a talking drawing application (Rector, Bartlett, & Mullan, 2018) that could guide them throughout the drawing process and eventually reduce the need for sighted assistance. According to the teachers, this format of audio description can be further simplified for experienced users by omitting the words Row

and Column and separating the numbers by a comma or short pause (Metatla et al., 2008). For instance, “Peg inserted, 1, 1 Filled”.

According to the majority of the participants, multimodal feedback that is both vibrotactile (device vibration) and non-verbal audio (beep sound) feedback should be provided immediately upon completion of the gestures or providing input. For instance, while performing a bend gesture with a threshold-based gesture completion strategy, immediately upon crossing the predefined threshold, both device vibration and beep sound should be provided to the user, followed by an audio description. According to the participants, having both feedback offers the confidence of not missing the feedback in an outdoor or noisy environment. The basic advantage of having vibrotactile feedback is that users do not have to be solely dependent on the auditory channel of perception to perceive the bend gesture completion. The vibrotactile feedback primarily works on an intimate private sensory channel (Brewster & Brown, 2004) and could be sufficient in a single-user environment. In terms of the prototype, the use of four vibration motors at the center of the device oriented towards the corners in direct physical contact with the 3D-printed internal structure of the prototype (as shown in 5.3a) enabled the participants to perceive the vibrotactile feedback uniformly across the silicone-cast prototype while holding it with either one or both hands. Such an arrangement of four vibration motors could also be utilized to trigger them independently or in pairs to provide spatial information, such as the location of bend gestures and navigation direction (Y. H. Lee & Medioni, 2014).

Since on-device vibration feedback requires the user to touch the device to perceive this feedback, providing only vibrotactile feedback in a multi-user training environment is insufficient. Also, according to the teachers, providing non-verbal audio (beep sound) feedback could be helpful in collaborative work with both visually impaired and sighted users. In this context, one teacher mentioned, “Having both audio and vibration feedback could be helpful in a classroom setting, especially while teaching new students to use the drawing tool by performing bend gestures or teaching how to perform a bend gesture at the very beginning”. Also, according to the teachers, new users of the tool must learn to work with both feedback systems so that they can easily and quickly adapt to the multi-user environment. However, according to them, after gaining a certain level of experience and expertise in using the tool, users may decide to turn OFF one or both (non-verbal audio and

vibrotactile) feedback according to their requirement provided audio description is always available after each input to inform or warn the users. Similar observations were also reported in the literature (Phillips & Proulx, 2018). In this context, one teacher said, "Since bend gestures themselves provide a good indication of the gesture end, after using the tool for a long period of time, users may not depend on such feedback to perceive that the gesture is complete". Taking all the rationales into account, in this work, we used both non-verbal audio and vibrotactile feedback considering their importance and their use reported in the existing literature (Bandyopadhyay & Rathod, 2017; Patil, Jawadwala, & Shu, 2018; S. Xu, Yang, Ge, Yu, & Shi, 2020). However, according to the teachers, users must have the option to make necessary changes in the feedback modalities. Similar findings regarding user suggestions for an option to customize the feedback modalities were also reported in the literature (Fernando & Ohene-Djan, 2021).

5.1.2.2 Findings on finalising the functions and their mappings with bend gestures and gesture completion strategies

In the second phase, the same groups of participants (Table 5.1) were involved during the study. The second phase aims to finalise the tool's basic and advanced functions. This phase also aims to map these functions with bend gestures and to finalise the bend gesture completion strategies to trigger associated functions. During this phase, the use of the keypad-based functional prototype with the feedback modalities (finalised in the previous phase), helped the participants to quickly experience the input interaction with the functions of the drawing application through bend gestures and decide the gesture completion strategies. The high-level themes that emerged during the analysis comprise gesture completion strategies, basic functions triggered with bend gestures (Set FOCUS, Navigate FOCUS, and Insert and Remove Peg), advanced functions to reduce effort, and trigger advanced functions with bend gestures and as menu items. Finally, the gestures and the gesture completion strategies that do not lead to ambiguous input are finalised and reported in Table 5.3.

5.1.2.2.1 Gesture completion strategies:

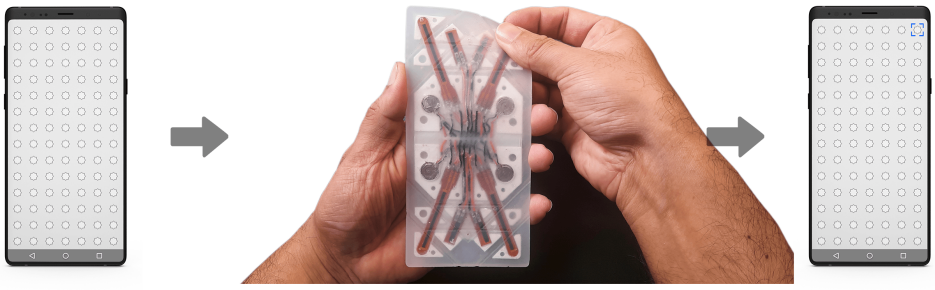
According to the participants, the threshold-based strategy is not suitable for triggering

critical functions such as “Remove All Pegs” and “Exit” functions. One participant mentioned, “I would prefer the threshold-based strategy for functions where consequences of triggering the function are easy to recover or does not bring any difference to the current drawing process”. This aligns with the findings reported in Section 4.2. However, according to the participants, the threshold-based strategy could be used to trigger critical functions if the gesture itself requires conscious effort. For instance, compound gestures could be combined with the threshold-based strategy. A few participants also mentioned using a larger threshold with a larger bend angle to trigger critical functions in addition to a smaller threshold. This aligns with the findings reported in Section 4.1 and Section 4.2. However, bending such large angles to achieve a larger threshold requires more physical effort; hence it is not considered for this study. We observed that the participants often showed the least preference for the On-Relax strategy for discrete input and the On-Quick-Relax strategy for continuous input. This also aligns with the findings reported in Section 4.2. All the participants confirmed the importance and potential use of implementing three types of hold-time (short, medium and long) for the On-Hold strategy. No difficulties and changes in the duration of short, medium and long hold-time were reported by the participants. However, according to the teachers, the short hold-time should be avoided in case of novice users of this bend gesture-based drawing tool to reduce mistakes.

5.1.2.2.2 Set the FOCUS at one of the corners:

We informed the participants that at the very start of the drawing process, the FOCUS would be at Row-1 and Column-1 which is the top-left corner hole of the grid. The participants found this grid-based drawing process natural and helpful similar to existing literature (Kamel & Landay, 2002b; Fernando & Ohene-Djan, 2021). They also reported that considering the top-left corner hole as the starting of the Row-count and Column-count resembles their usual practice of using this hole as the starting point. However, the majority agreed that they would prefer the option of choosing any of the four corner holes as their initial starting point. No holes should be in FOCUS at the start of the application, and the user should get to choose which corner hole should become the starting hole in FOCUS. According to the participants, this process of selecting the initial corner hole to set FOCUS before starting the drawing resembles selecting a hole on the pegboard before inserting any peg. This also allows users to build an

allocentric spatial mental model (Grech, Nakamura, & Hill, 2018) throughout the drawing, starting from the selection of the first corner hole. Such an allocentric spatial mental model helps users to successfully reach an intended location irrespective of the current location of the user (Grech et al., 2018). As a result, another basic function named "Set FOCUS at a Corner" has been added to the final list of functions (Table 5.3). According to the participants, bending a corner downward with a large size and holding the bend for a moment resembles pulling the FOCUS to that corner. One participant mentioned, "it feels like I am dragging the FOCUS to the corner in one large step". As a result, a Bend-downward Large-size gesture at respective corners with an On-hold gesture completion strategy of long hold-time is mapped to this function. For instance, performing the gesture at the top-right corner (Figure 5.5), bottom-right corner (Figure 5.6), bottom-left corner (Figure 5.7), and top-left corner (Figure 5.8) will set the FOCUS at respective corners. The use of an on-hold strategy also reduces the possibility of unwanted or unintended input (as reported in Section 4.2). According to the participants, this function could also be helpful during drawing. For instance, during drawing, the user might need to quickly navigate to one of the corner holes, which can be achieved through the "Set FOCUS at a Corner" function.



Function: Set FOCUS at Top-right Corner
Bend gesture: Top-right-corner Bend-downward Large-size
Gesture completion strategy: Long On-Hold (3 Sec)
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Selected, Row-1 Column-7 Empty"

Figure 5.5: A user is performing the Top-right-corner Bend-downward Large-size gesture combined with the Long On-Hold (3 Sec) gesture completion strategy to set the FOCUS at the top-right corner.

Function: Set FOCUS at Bottom-right Corner
Bend gesture: Bottom-right-corner Bend-downward Large-size
Gesture completion strategy: Long On-Hold (3 Sec)
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Selected, Row-14 Column-7 Empty"

Figure 5.6: A user is performing the Bottom-right-corner Bend-downward Large-size gesture combined with the Long On-Hold (3 Sec) gesture completion strategy to set the FOCUS at the bottom-right corner.

Function: Set FOCUS at Bottom-left Corner
Bend gesture: Bottom-left-corner Bend-downward Large-size
Gesture completion strategy: Long On-Hold (3 Sec)
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Selected, Row-14 Column-1 Empty"

Figure 5.7: A user is performing the Bottom-left-corner Bend-downward Large-size gesture combined with the Long On-Hold (3 Sec) gesture completion strategy to set the FOCUS at the bottom-left corner.

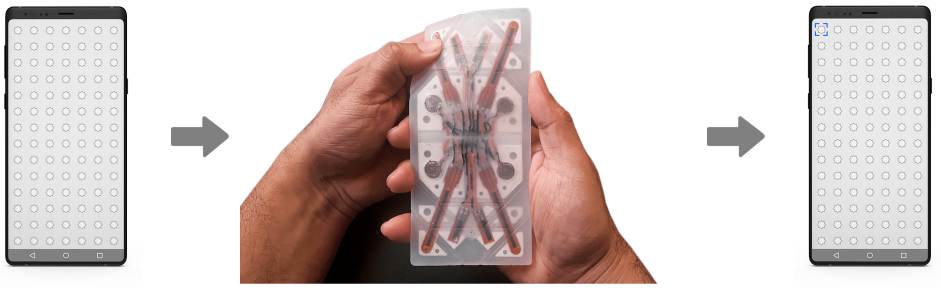


Figure 5.8: A user is performing the Top-left-corner Bend-downward Large-size gesture combined with the Long On-Hold (3 Sec) gesture completion strategy to set the FOCUS at the top-left corner.

5.1.2.2.3 Navigate the FOCUS towards one of the eight directions:

For navigating the FOCUS from one digital hole to another, all the participants agreed with the basic need to navigate in eight directions. These eight directions are navigating towards the right, bottom, left, top, bottom-right, bottom-left, top-left, and top-right directions (Kamel & Landay, 1999, 2002b). Participants were also able to perceive the inherent directional cues of bend gestures (Borah, Seth, & Sorathia, 2021) and relate them with the directions of navigation. As a result, the majority-proposed bend gestures for the navigation functions toward eight directions have spatial directional similarity with the directions of navigation (listed in Table 5.3). According to the participants bending the flexible device upward (that is bending towards the user) gives the perception of pushing the FOCUS away from the location of the bend gesture, while bending downward (that is bending away from the user) gives the perception of pulling the FOCUS towards the location of the bend gesture. As a result, for each navigation function, a pair of gestures were proposed by the participants. For instance, to move the FOCUS towards the right by one step, the majority of the participants proposed using either the Top-left-corner Bend-upward Small-size gesture (to push the FOCUS towards the right) or the Top-right-corner Bend-downward Small-size gesture (to

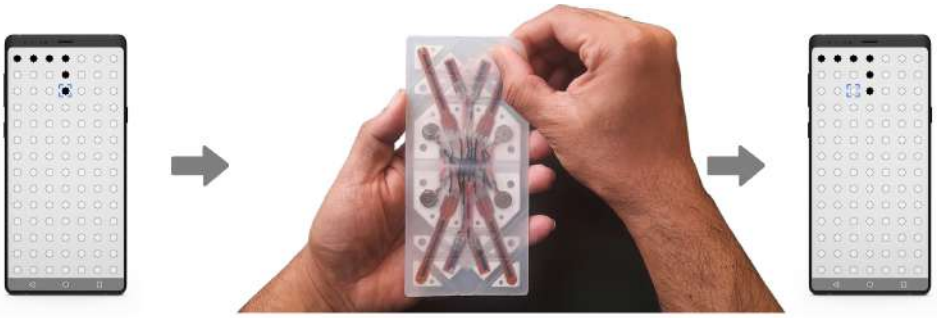
pull the FOCUS towards the right). According to the teachers, having both push and pull gestures for a single navigation function could confuse the students who do not have enough experience using the tool or are novice users. Moreover, since bending upward is easy to perform according to our findings reported in Section 4.1 and existing literature (Warren et al., 2013; Girouard et al., 2015), and navigation is a frequently performed function, only upward gestures were considered for the navigation function for further evaluation. As reported in Table 5.3, bend gestures of small size at top corners are mapped to horizontal navigation functions (Figure 5.9 and 5.10), bend gestures of small size at top and bottom sides are mapped to vertical navigation functions (Figure 5.11 and 5.12), and bend gestures of large size at corners are mapped to diagonal navigation functions (Figure 5.13, 5.14, 5.15, and 5.16). Here all the implemented gestures are Bend-upward gestures. However, a few participants suggested adding the Top-side Bend-downward Small-size gesture for navigating towards the top. They suggested that this will reduce hand re-gripping during drawing since both horizontal and vertical navigation can be performed by holding the top locations. This aligns with the findings reported in the literature (Kildal & Boberg, 2013) regarding reduced re-gripping during bend gesture-based interaction. This also aligns with the findings reported in Chapter 3, where we found that differentiating and performing two magnitude levels of size-based gestures at top locations is easier than at bottom locations. According to the teachers, the Top-side Bend-downward Small-size gesture should be kept associated with the "Navigate FOCUS Towards Top" function so that experienced users can utilize it later. In light of the above, we kept downward bend gestures reserved for mapping with "Navigate FOCUS" functions in the future. However, currently, for evaluation of the tool, only Bend-upward gestures were considered and implemented for the navigation functions. In addition, although a digital drawing tool could provide an infinite grid, these navigation gestures could be performed both at an intermediate as well as at a boundary position (of a finite grid). In this context, performing the navigation gestures at a boundary position could provide warning audio description feedback, as shown in Figure 5.17. However, the on-device vibrotactile feedback and the non-verbal audio (beep sound) feedback remained the same as they only indicated the completion of bend gestures in this research work.

In Chapter 4, we identified that bending with a small magnitude level of size-based gestures at the top and bottom sides by holding a small region requires relatively more effort

than bending with a large magnitude level of size. In contrast, in this study, the participants preferred to use the small size of bend gestures at the top and bottom sides due to the use of modified internal structure (Figure 5.3a) and presence of grooves Figure 5.3b) on the silicone cast functional prototype that allowed participants to bend the device with reduced effort. This aligns with the findings reported in Chapter 4, regarding the need for ease of performing and differentiation of two magnitude levels. According to the participants of this participatory design study, the grooves on the surfaces of the silicone cast functional prototype offer both ease of differentiation and ease of performing two magnitude levels at the corners and top and bottom sides. According to the participants, these navigation functions should be triggered as soon as a predefined bend (or threshold of bend angle) is crossed while performing respective bend gestures. Since navigation is a frequently used function and the outcome produced by triggering this function does not lead to major changes, the threshold-based gesture completion strategy will enable them to provide quick input during navigation.

Function: Navigate FOCUS Towards Right
Bend gesture: Top-left-corner Bend-upward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Moved towards right, Row-3 Column-5 Empty"

Figure 5.9: A user is performing the Top-left-corner Bend-upward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to horizontally navigate the FOCUS towards the right.



Function: Navigate FOCUS Towards Left
Bend gesture: Top-right-corner Bend-upward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Moved towards left, Row-3 Column-3 Empty"

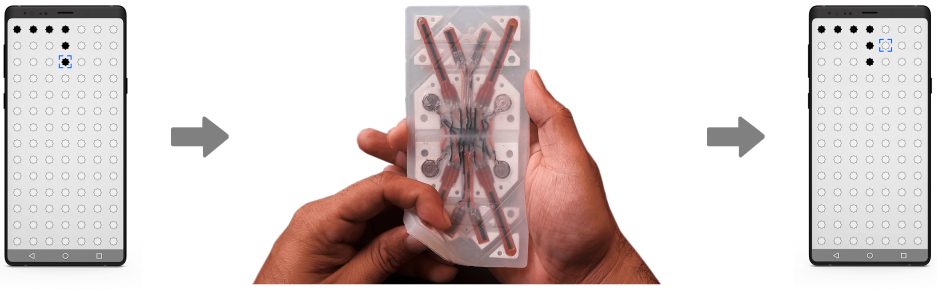
Figure 5.10: A user is performing the Top-right-corner Bend-upward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to horizontally navigate the FOCUS towards the left.

Function: Navigate FOCUS Towards Top
Bend gesture: Bottom-side Bend-upward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Moved towards top, Row-2 Column-4 Filled"

Figure 5.11: A user is performing the Bottom-side Bend-upward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to vertically navigate the FOCUS towards the top.

Function: Navigate FOCUS Towards Bottom
Bend gesture: Top-side Bend-upward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Moved towards bottom, Row-4 Column-4 Empty"

Figure 5.12: A user is performing the Top-side Bend-upward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to vertically navigate the FOCUS towards the bottom.

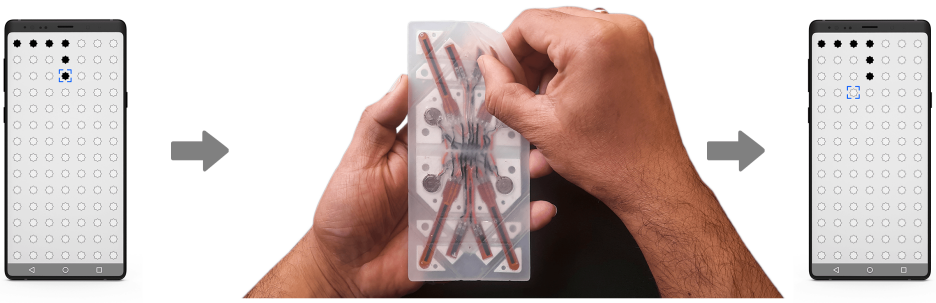


Function: Navigate FOCUS Towards Top-right
Bend gesture: Bottom-left-corner Bend-upward Large-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Moved towards Top-right, Row-2 Column-5 Empty"

Figure 5.13: A user is performing the Bottom-left-corner Bend-upward Large-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to diagonally navigate the FOCUS towards the top-right corner.

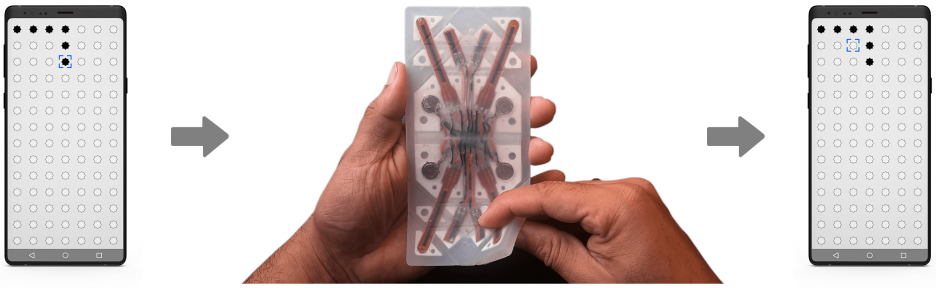
Function: Navigate FOCUS Towards Bottom-right
Bend gesture: Top-left-corner Bend-upward Large-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Moved towards bottom-right, Row-4 Column-5 Empty"

Figure 5.14: A user is performing the Top-left-corner Bend-upward Large-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to diagonally navigate the FOCUS towards the bottom-right corner.



Function: Navigate FOCUS Towards Bottom-left
Bend gesture: Top-right-corner Bend-upward Large-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Moved towards bottom-left, Row-4 Column-3 Empty"

Figure 5.15: A user is performing the Top-right-corner Bend-upward Large-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to diagonally navigate the FOCUS towards the bottom-left corner.



Function: Navigate FOCUS Towards Top-left
Bend gesture: Bottom-right-corner Bend-upward Large-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Moved towards Top-left, Row-2 Column-3 Empty"

Figure 5.16: A user is performing the Bottom-right-corner Bend-upward Large-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to diagonally navigate the FOCUS towards the top-left corner.

Function: Navigate FOCUS Towards Right
Bend gesture: Top-left-corner Bend-upward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Can't move further towards right, Row-3 Column-7 Empty"

Figure 5.17: A user is performing the Top-left-corner Bend-upward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to horizontally navigate the FOCUS towards the right. Here, the FOCUS can not be moved beyond the predefined grid of size 14 rows and 7 columns. A warning audio description is provided to the user. (Coloured Figure)

5.1.2.2.4 Insert and remove peg at the current hole in FOCUS:

For inserting and removing digital pegs, all the participants proposed using bipolar gestures (Ahmaniemi et al., 2014). For instance, upward gestures for peg insertion and downward gestures for peg removal. To make the peg insertion and removal gestures distinct from the navigation gestures with higher conscious effort, the majority of the participants proposed bending both top corners together. According to the participants, the circular path followed while bending the top corners towards the upward direction gives the perception of or enables them to relate to the metaphor of pushing a physical peg with both hands to insert in the current hole in FOCUS. As a result, the Top-corners Bend-upward Small-size gesture is mapped to the "Insert Peg" function as shown in Figure 5.18. Conversely, to remove a peg, the participants proposed the opposite direction of the bend, which is bending the device's both top corners towards the downward direction. As a result, the Top-corners Bend-downward Small-size gesture is mapped to the "Remove Peg" function as shown in Figure 5.19. One disadvantage of this compound gesture is the need for simultaneous use of both hands to bend both top corners, which is not suitable for one-handed interaction. However, the users' natural way of interacting with the physical pegboard with both hands (Chapter 3) motivated us to include the proposed bend gesture. The use of bi-manual interaction for tangible graph construction and browsing was also reported in the literature (D. McGookin et al., 2010). In addition, the associated conscious effort in performing the compound gesture reduces the possibility of unwanted or unintended input. According to the participants, these functions should be triggered as soon as a predefined bend (or threshold) is crossed while performing the bend gestures. Although peg insertion and removal can bring moderate to severe changes in the outcome of the drawing process, the participants selected the threshold-based strategy considering the conscious effort required in performing the compound gestures.

Moreover, a user can perform these gestures to trigger "Insert Peg" or "Remove Peg" functions irrespective of the status of the current hole in FOCUS. If the current hole in FOCUS already has a peg in it, in this context, performing the insert peg compound gesture will provide warning audio description feedback (Figure 5.20). Similarly, if the current hole in FOCUS is already empty, in this context, performing the remove peg compound gesture will provide warning audio description feedback (Figure 5.21). However, the on-device vibrotactile feedback and the non-verbal audio (beep sound) feedback remained the same.

Function: Insert Peg
Bend gesture: Top-corners Bend-upward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Peg inserted, Row-4 Column-4 Filled"

Figure 5.18: A user is performing the Top-corners Bend-upward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to insert a peg.

Function: Remove Peg
Bend gesture: Top-corners Bend-downward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Peg removed, Row-4 Column-4 Empty"

Figure 5.19: A user is performing the Top-corners Bend-downward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to remove a peg.

Function: Insert Peg
Bend gesture: Top-corners Bend-upward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Can't insert, Row-4 Column-4 already Filled"

Figure 5.20: A user is performing the Top-corners Bend-upward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to insert a peg. Here, the peg can not be inserted as the current hole in FOCUS is already filled. A warning audio description is provided to the user. (Coloured Figure)

Function: Remove Peg
Bend gesture: Top-corners Bend-downward Small-size
Gesture completion strategy: On-Crossing a Threshold
Feedback modalities:
On-device vibrotactile feedback
Non-verbal audio (beep sound) feedback
Audio description: "Can't remove, Row-4 Column-4 already Empty"

Figure 5.21: A user is performing the Top-corners Bend-downward Small-size gesture combined with On-Crossing a Threshold (or threshold-based) gesture completion strategy to remove a peg. Here, the peg can not be removed as the current hole in FOCUS is already empty. A warning audio description is provided to the user. (Coloured Figure)

5.1.2.2.5 Advanced functions to reduce effort:

We also requested the participants to share their opinions on the need for additional functions to easily accomplish the digital drawing task resembling their mental model of using the existing pegboard-based drawing process. The participants reported that navigation and peg insertion as two separate steps make the drawing process simple and eventually easy to understand and learn for new users. However, this repetitive process requires more time and effort, and also, for an experienced user of the tool, there should be an alternative to achieve the same without performing repeated gestures. One teacher with visual impairment mentioned, "This repetitive process is good for beginners. However, experienced users might find this repetitive process annoying and time-consuming". One student mentioned, "After gaining sufficient experience with the tool, I should no longer be required to follow this repetitive procedure". Participants' verbal responses indicate a need for flexibility of use (Nielsen, 2020). In this context, we asked the participants to practice the tool multiple times and explore intuitive ways to reduce repeated input to save both time and effort during the drawing process. The participants reported additional advanced functions to make the drawing process less time-consuming. The participants suggested two ways to reduce repeated gesture-based input once a user gains adequate experience using the basic functions. These two proposed ways target to eliminate the repeated input during peg insertion and FOCUS navigation, respectively.

The first way of achieving this goal is by inserting only the two end pegs of a straight line, and the intermediate pegs of the straight line are inserted automatically. We named this function "Join Between Two Pegs". According to the participants, this function can be triggered by performing the insert peg gesture combined with an on-hold strategy of medium hold-time. To reverse this trigger, the user can perform the gesture for the "Remove peg" function at the same position or perform the "UNDO" function. Once the "Join Between Two Pegs" function is triggered, the first peg is inserted at the current grid position in FOCUS, and after that user can keep on navigating in a direction up to the intended distance. On reaching the other end of the straight line, the user performs the same insert peg gesture combined with the same on-hold strategy of medium hold-time to insert a peg that also indicates the end of the straight line. The insertion of the last peg also triggers the auto-insertion of the intermediate pegs.

The second way of eliminating repeated bend gestures proposed by the participants is to continuously keep on navigating in a direction by combining the On-Hold strategy of

medium hold-time with the respective bend gesture for the “Navigate FOCUS” function. For instance, if the user wants to navigate multiple holes towards the left direction, then the user will perform the Top-right-corner Bend-upward Small-size gesture, and after crossing the predefined threshold for the angle of bend, the user will keep holding that bend gesture without releasing it. Holding this navigation gesture for more than the duration of medium hold-time will trigger the respective advanced function, and the FOCUS will start to move one by one (with a short intermediate delay to provide grid information) towards the left until the user releases the bend gesture. Here the On-release gesture completion strategy indicates the end of the continuous navigation. We named this function “Continuous Navigation”. In addition, the participants reported the potential combined use of “Join Between Two Pegs” and “Continuous Navigation” functions to make the drawing process easy and time efficient.

The participants also mentioned that if they pause drawing for an interval, they might lose track of the counting for grid positions while the drawing is resumed. In such a case, the device should enter into the standby mode, and on performing the Vertical-axis-of-symmetry Bend-downward gesture combining the On-Hold strategy of medium hold-time, the device will wake up by reading out aloud the grid position currently in FOCUS. We named this function “Wake-up with Position Info”. According to the teachers, users must have the option to turn ON or OFF the advanced functions that demand prior experience in drawing or using the tool.

5.1.2.2.6 Trigger advanced functions with bend gestures and as menu items:

After finalising the bend gestures for the list of basic functions and advanced functions to reduce effort, we focused on the initial set of advanced functions (Table 5.2). The advanced functions could cater to the experienced user group to improve their performance by taking advantage of the digital platform. Although these advanced functions are not a part of the immediate prototype, we aimed to identify the potential techniques to trigger these advanced functions.

While frequently used functions are triggered with bend gestures, additional functions of the digital tool can be triggered by selecting them as a menu item (Miller, 2006). According to the participants, these functions should be presented as a common vertical list of items or a vertical menu of items. Although opening and navigating a menu can be done using other input techniques, considering the inherent tactile and kinesthetic feedback (Wightman et al.,

2011) and directional cue of bend gestures (Borah, Seth, & Sorathia, 2021), we aimed to identify a set of bend gestures that can complement the other interaction techniques. All the participants enjoyed exploring the potential of bend gestures and relating them to real-world metaphors. In this context, according to the participants, bending the device at the Vertical-axis-of-symmetry towards the downward direction (Figure 5.1) resembles the real-world metaphor of opening a door that can be mapped to the "Open Menu" function. Conversely, according to the participants, the Vertical-axis-of-symmetry Bend-upward gesture (Figure 5.1) can be mapped to the "Close Menu" function. Considering a common vertical list of items or vertical menu of items, participants preferred to reuse the gestures selected for "Navigate Towards Top" and "Navigate Towards Bottom" for "Navigate a List Towards Top" and "Navigate a List Towards Bottom" functions. Likewise, for "Confirm" and "Cancel" (or Reject) functions, the majority of the participants proposed reusing the gestures proposed for "Insert Peg" and "Remove Peg" functions correspondingly, considering the conscious effort required to perform these gestures. According to the participants, these functions should be triggered as soon as a predefined bend (or threshold of bend angle) is crossed while performing respective bend gestures.

According to the participants, functions that are least frequently used should appear as menu items. These functions include New Board, Open Board, Rename Board, Save As, UNDO, REDO, Label a Grid Position, Clear All Pegs, Help, and Exit. However, considering the importance of "UNDO" and "REDO" functions that provide flexibility of use (Nielsen, 2020), we asked the participants to identify appropriate gestures for them that are easy to perform and intuitive. According to the participants, bending the device at the Horizontal-axis-of-symmetry towards the downward direction with On-Crossing a Threshold (or threshold-based) gesture completion strategy should trigger the "UNDO" function. Conversely, bending towards the upward direction that is performing the Horizontal-axis-of-symmetry Bend-upward gesture with On-Crossing a Threshold (or threshold-based) gesture completion strategy should trigger the "REDO" function (if UNDO has already been triggered). We also asked the participants to identify an appropriate gesture for "Clear All Pegs" function. The participants proposed to reuse the gesture for the "Remove Peg" function combined with the On-Hold strategy of long hold-time to trigger the "Clear All Pegs" function that demands a considerable conscious effort before gesture completion.

5.1.3 Design of Naamya

The motivation behind investigating the use of bend gestures for drawing primitive geometric shapes is to overcome the limitations of analogue drawing tools and input modalities that do not offer both tactile feedback and association with spatial directions. In this research work, the bend gesture-based smartphone-sized geometric shape drawing tool (Naamya) is designed using human-centred design approaches. This smartphone-sized flexible handheld tool is designed to accomplish geometric shape drawing where users can provide input to the system by performing bend gestures. With the ability to provide input by bending the device, which offers inherent tactile and kinesthetic feedback and association with spatial directional cues, we believe this will be helpful for users with blindness or low vision to perform drawing tasks. The word Nāmya is a Sanskrit word that means bendable, pliant, pliable, or flexible (Monier-Williams, 1964; Apte, 1965; Macdonell, 2004). The second letter ā (Latin A with a macron) denotes the long vowel to pronounce the word as Naamya.

We designed Naamya with our understanding of the current pegboard-based drawing tools to match the user's existing mental model. The basic functions included in the current design of Naamya are presented in Table 5.3. Although both basic and advanced functions were explored during the participatory design study, for this research, we have limited the implementation to the basic functions. These basic functions are essential to accomplishing the drawing task of primitive geometric shapes such as squares, rectangles, and triangles. These basic functions include setting FOCUS at corners, navigating towards eight cardinal directions, inserting a peg and removing a peg. As reported in the third column of Table 5.3, during this participatory design study, the basic functions are mapped to fourteen unique bend gestures (presented in Figure 5.22) considering the similarity between the directional cue of the bend gestures and the directions or user-perceived directions associated with the functions. Later, two gesture completion strategies (Long On-Hold and On-Crossing a Threshold, as reported in the fourth column of Table 5.3) are utilized to indicate the completion of the bend gestures primarily based on the changes in the output resulting from triggering the functions and the frequency of using the functions.

We finalised the feedback modalities based on the findings of the participatory design study. We utilized three feedback modalities, on-device vibrotactile feedback, non-verbal audio (beep sound) feedback, and audio description. We utilized the audio description with

context-specific content to provide both information regarding the progress in drawing and warning during drawing. However, the on-device vibrotactile feedback and the non-verbal audio (beep sound) feedback are not utilized to provide information regarding the progress in drawing or warning during drawing. These two feedback modalities (vibrotactile and non-verbal audio) are used only to indicate the completion of bend gestures. For further evaluation, we utilized the functional prototype shown in Figure 5.3d with three feedback modalities, fourteen gesture function mappings, and two gesture completion strategies.

Figure 5.22: Fourteen unique bend gestures mapped to the basic functions of Naamya.

Table 5.3: List of basic and advanced functions and the ways to trigger these functions. Functions marked with asterisk (*) are newly added functions.

Function name	Level	Trigger by bend gesture or as a menu item	Gesture completion strategy
Set FOCUS at Top-right Corner*	Basic	Top-right-corner Bend-downward Large-size	Long On-Hold (3 Sec)
Set FOCUS at Bottom-right Corner*	Basic	Bottom-right-corner Bend-downward Large-size	Long On-Hold (3 Sec)
Set FOCUS at Bottom-left Corner*	Basic	Bottom-left-corner Bend-downward Large-size	Long On-Hold (3 Sec)
Set FOCUS at Top-left Corner*	Basic	Top-left-corner Bend-downward Large-size	Long On-Hold (3 Sec)
Navigate FOCUS Towards Right	Basic	Top-left-corner Bend-upward Small-size	On-Crossing a Threshold
Navigate FOCUS Towards Left	Basic	Top-right-corner Bend-upward Small-size	On-Crossing a Threshold
Navigate FOCUS Towards Top	Basic	Bottom-side Bend-upward Small-size	On-Crossing a Threshold
Navigate FOCUS Towards Bottom	Basic	Top-side Bend-upward Small-size	On-Crossing a Threshold
Navigate FOCUS Towards Top-right	Basic	Bottom-left-corner Bend-upward Large-size	On-Crossing a Threshold
Navigate FOCUS Towards Bottom-right	Basic	Top-left-corner Bend-upward Large-size	On-Crossing a Threshold
Navigate FOCUS Towards Bottom-left	Basic	Top-right-corner Bend-upward Large-size	On-Crossing a Threshold
Navigate FOCUS Towards Top-left	Basic	Bottom-right-corner Bend-upward Large-size	On-Crossing a Threshold
Insert Peg	Basic	Top-corners Bend-upward Small-size	On-Crossing a Threshold
Remove Peg	Basic	Top-corners Bend-downward Small-size	On-Crossing a Threshold
Open Menu	Advanced	Vertical-axis-of-symmetry Bend-downward	On-Crossing a Threshold
Close Menu	Advanced	Vertical-axis-of-symmetry Bend-upward	On-Crossing a Threshold
Navigate a List Towards Top	Advanced	Bottom-side Bend-upward Small-size	On-Crossing a Threshold
Navigate a List Towards Bottom	Advanced	Top-side Bend-upward Small-size	On-Crossing a Threshold
Confirm	Advanced	Top-corners Bend-upward Small-size	On-Crossing a Threshold
Cancel or Reject	Advanced	Top-corners Bend-downward Small-size	On-Crossing a Threshold
New Board	Advanced	As a Menu Item	-
Open Board	Advanced	As a Menu Item	-
Rename Board	Advanced	As a Menu Item	-
Save As	Advanced	As a Menu Item	-
UNDO	Advanced	As a Menu Item or Horizontal-axis-of-symmetry Bend-downward	- On-Crossing a Threshold
REDO	Advanced	As a Menu Item or Horizontal-axis-of-symmetry Bend-upward	- On-Crossing a Threshold
Label a Grid Position	Advanced	As a Menu Item	-
Clear All Pegs	Advanced	As a Menu Item or Top-corners Bend-downward Small-size	- Long On-Hold (3 Sec)
Help	Advanced	As a Menu Item	-
Exit	Advanced	As a Menu Item	-
Join Between Two Pegs*	Advanced	Top-corners Bend-upward Small-size	Sequence of strategies
Continuous Navigation*	Advanced	Gestures assigned for “Navigate FOCUS” functions	Sequence of strategies
Wake-up with Position Info*	Advanced	Vertical-axis-of-symmetry Bend-downward	Medium On-Hold (1.5 Sec)

5.2 Evaluation of Naamya

Section 5.1 presented the design of Naamya using a participatory design approach by finalising the feedback modalities and functions of the drawing tool and mapping these functions with bend gestures and gesture completion strategies. This section details the user study that aims to evaluate the effectiveness of using a bend gesture-based digital drawing tool for creating simple and compound primitive geometric shapes including squares, rectangles, and triangles. A previous study (reported in Chapter 3) revealed that pegboard-based tools are the commonly used tools for drawing by school students with blindness or low vision, in particular the Taylor Arithmetic Slate. This study compared the bend gesture-based digital drawing tool (Naamya) with a pegboard-based tool (Taylor Arithmetic Slate). The findings of this study answer the last research question "RQ 5: Does a bend gesture-based geometric shape drawing tool enable BLV users to draw primitive geometric shapes effectively compared to the existing drawing tool?" (RQ 5 reported in Section 1.2).

5.2.1 Methodology

5.2.1.1 Participants

For participants with blindness or low vision, we contacted two academic institutes requesting students' voluntary participation. The criteria for participation were to have a minimum of three years of experience using smartphones through touch gestures of screen readers. Their percentage of visual impairments is 70% or more with no upper limb disorder, according to participants' medical certificates. They have learned to draw primitive geometric shapes in the curriculum. Twenty students (12 male and 8 female) between the ages of 18-25 years (Mean = 20, SD = 2.29) participated in the study. All the students have at least three years of experience using Android smartphones using Google TalkBack. The demographic information of the participants is reported in Table 5.4.

Table 5.4: Demographic information of the participants.

Participant	Age	Gender	Handedness	Visual impairment (%)	Impairment since	Perception of light
P1	21	M	Right	100	13 years old	Yes
P2	18	F	Right	100	2 years old	Yes
P3	18	M	Right	80	7 years old	Yes
P4	19	M	Right	90	1 year old	Yes
P5	18	M	Right	80	Birth	Yes
P6	23	M	Left	100	6 years old	No
P7	18	M	Left	80	2 years old	Yes
P8	25	M	Right	100	2 years old	No
P9	18	F	Right	100	Birth	Yes
P10	18	F	Right	80	Birth	Yes
P11	18	F	Right	100	Birth	Yes
P12	18	F	Right	100	7 years old	No
P13	23	F	Right	80	Birth	Yes
P14	23	F	Right	100	Birth	No
P15	21	M	Right	100	Birth	Yes
P16	19	M	Left	100	9 years old	Yes
P17	21	M	Left	100	Birth	Yes
P18	23	M	Right	100	Birth	Yes
P19	19	M	Right	80	11 years old	Yes
P20	19	F	Right	100	Birth	Yes

5.2.1.2 Task

We asked the participants to perform five drawing tasks (T1, T2, T3, T4, and T5). The first three tasks (T1, T2, T3) include drawing simple primitive geometric shapes such as squares, rectangles and triangles. The rest two tasks (T4 and T5) include drawing compound shapes, consisting of primitive shapes. In the first compound shape (T4 in Figure 5.23a), a square (3x3 pegs) is placed inside another square (6x6 pegs) without any shared edges between the primitive shapes. In the second compound shape (T5 in Figure 5.23b), an isosceles triangle (base 5 pegs long) lying on the top of a rectangle (height 4 and width 5 pegs) with a shared edge between the primitive shapes.

T1: Draw a square with minimum 4x4 pegs.

T2: Draw a rectangle with height 4 and width 5 pegs.

T3: Draw a triangle with a base 5 pegs long.

T4: Draw a compound shape, consisting of a square inside another square exactly as instructed through the tactile card 1 (Figure 5.23a).

T5: Draw a compound shape, consisting of a triangle on top of a rectangle exactly as instructed through the tactile card 2 (Figure 5.23b).

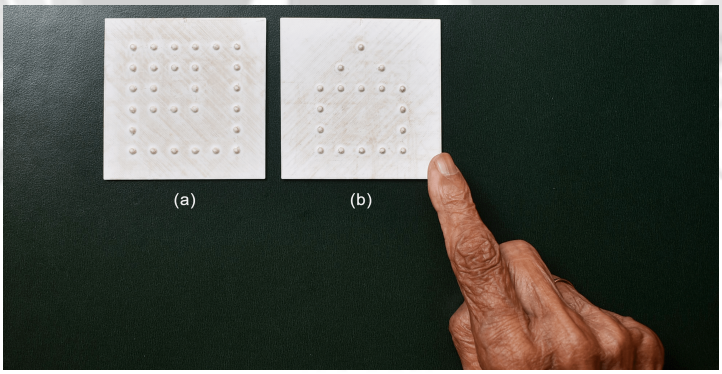
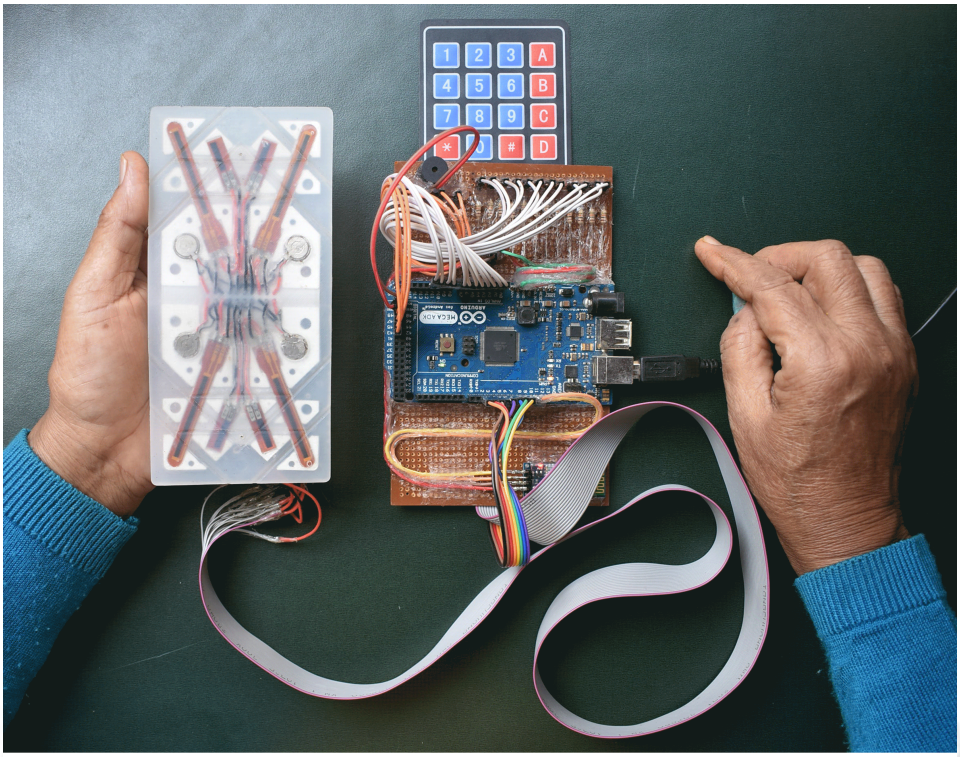


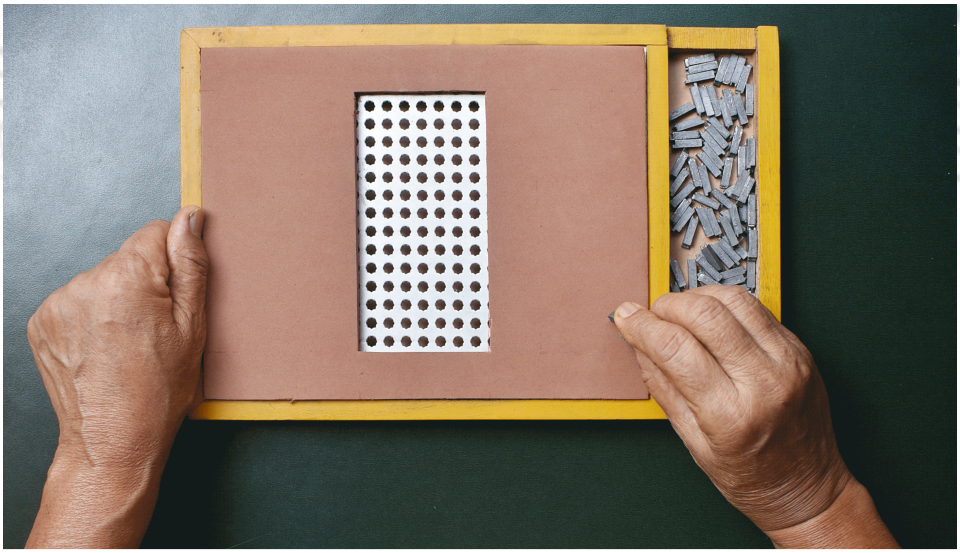
Figure 5.23: Two 3D-printed tactile cards to represent compound shapes. (a) Tactile card 1: a square inside another square and (b) Tactile card 2: a triangle on top of a rectangle.

5.2.1.3 Apparatus

The study was conducted using Naamya, a smartphone-sized flexible functional prototype (Figure 5.24a) designed through a participatory design approach (reported in Section 5.1). The prototype measures 6.7 inches (170 mm) at the diagonal and the dimension of the prototype (154 mm x 74 mm x 7 mm) was decided to match the size of commonly used smartphones. We restricted the digital space to a smaller grid of size 14 rows and 7 columns to match the ratio with a smartphone-sized device in portrait mode. This also allowed ease of navigation within a limited digital space with limited information to store in the working memory of the participants. Similar to existing literature (Fernando & Ohene-Djan, 2022), we also decided to compare the proposed bend gesture-based digital drawing tool with an analogue tool considering their everyday use. We selected the Taylor Arithmetic Slate for comparison because it is one of the commonly used pegboard-based tools for drawing (identified in Section 3.1). We used a Taylor Arithmetic Slate containing a grid of physical holes of size 18 rows and 25 columns. Students with visual impairment or blindness use this for geometric shape drawing by inserting pegs into the grid of 18x25 holes. However, to balance the mental model of the participants in using Naamya and Taylor Arithmetic Slate for drawing purposes, as shown in Figure 5.24b, we restricted the participants to use a physical grid of size 14 rows and 7 columns at the center of the board. We achieved this by covering the rest of the physical holes on the Taylor Arithmetic Slate by using an EVA foam sheet of thickness 3mm. We selected the center of the Taylor Arithmetic Slate to keep it available for drawing to offer a consistent experience of touching the EVO foam as the border of this smaller physical grid.



(a)



(b)

Figure 5.24: (a) Functional prototype of the bend gesture-based digital drawing tool (Naamya) and (b) pegboard-based tool (Taylor Arithmetic Slate) covered with EVA foam.

5.2.1.4 Procedure

All the participants have given informed consent to participate in this research work voluntarily. We conducted the study in a controlled environment in the school of the students (Figure 5.25). After explaining the purpose of this study, demographic information is collected. As we identified and reported in Chapter 3, students avoid geometric drawings of their curriculum. As a result, the majority of the participants have limited to minimal knowledge of drawing primitive geometric shapes. In addition, no students have prior knowledge of using row and column numbers to refer to the grid positions during pegboard-based drawing. Therefore, we organised a five-day training session in the native language (Assamese language) before conducting the study. The first two days of the training session included learning primitive geometric shapes (square, rectangle, and triangle) and learning to refer to the grid positions using row and column numbers. The rest three days of the training session included learning the bend gesture-based drawing tool and practising primitive geometric shape drawing on both bend gesture-based and pegboard-based tools. The dimensions of the primitive shapes used in the experiment's tasks (T1, T2, and T3) were excluded during the entire training session.

Figure 5.25: A student is sitting in front of the moderator and holding the bend gesture-based tool (Naamya) to perform the drawing tasks.

After completion of the training session, when the participants reported themselves as ready and comfortable to participate in the study, we explained the objective of this comparative study. Then we explained and helped each participant to understand the tasks, in particular, the compound drawing tasks (T4 and T5). As assessing the participants' ability to read tactile cards was not the objective of this study, we assisted them as much as possible to correctly interpret the tactile cards (Figure 5.23) by holding their hands and fingers. After participants confirmed their comprehension of all drawing tasks, we asked them to complete the tasks using both the bend gesture-based digital drawing tool (Naamya) and the pegboard-based drawing tool (Taylor Arithmetic Slate). The sequence of the tools was altered for every next participant. After providing the tool, we asked the participants to speak aloud about how they intended to complete the task while drawing. We did not correct the participants if their reported intention was incorrect until they reported any trouble in completing the drawings after traversing the drawing on their own to identify the error. On reporting such trouble in completing the tasks, we provided minimal assistance to overcome the error. This minimal assistance primarily includes asking the participants to verify perpendicular, diagonal, straight, or parallel lines and the length of a straight line. After completing all the tasks on one tool, the participants rated on a 7-point Likert scale for ten statements (S1-S10) mentioned below. The seven points of the Likert scale comprise: 1-Strongly Disagree, 2-Disagree, 3-Somewhat Disagree, 4-Neither Agree Nor Disagree, 5-Somewhat Agree, 6-Agree, and 7-Strongly Agree. With the participants' permission, we read out the statements and the seven points of the Likert scale aloud. An informal discussion follows this to understand the reasons behind the ratings and their experience using the tool. The same process was repeated for both tools. After completing the drawing tasks on both tools, we asked the participants to share their confidence during drawing, preferred drawing tool provided sufficient training is facilitated, and the requirement for any further training. With the knowledge gained from existing literature (reported in Chapter 2) and previous studies, we formulated and used the below-mentioned ten statements (S1-S10) instead of other standard tools of usability in order to comprehend the user's drawing experience using the bend gesture-based digital drawing tool Naamya.

S1: I think this tool is easy to use.

S2: I think this tool is easy to learn.

S3: I found that this tool encourages me to continue practising drawings.

S4: I felt very confident in correctly drawing straight lines using this tool.

S5: I felt very confident in selecting the next intended hole correctly using this tool.

S6: I found that this tool allows me to easily perceive the change in the direction of progress.

S7: I think this tool is error-proof to the wrong next-hole selection.

S8: I found that I can easily navigate from one hole to another using this tool.

S9: I found that this tool enables me to correctly navigate from one hole to another.

S10: I found that this tool allows me to easily build a spatial layout model of the drawing in my mind.

5.2.2 Results and findings

In this study, we aimed to investigate the effectiveness of the bend gesture-based digital drawing tool Naamya as compared to the pegboard-based drawing tool Taylor Arithmetic Slate. We recorded the drawings to observe the drawing tasks and errors. Later we calculated the number of successful completion of the tasks (with and without assistance), number of errors, and types of errors. We also collected the responses of the participants to the Likert scale statements. Since the collected data are not normally distributed, we used a non-parametric test, the Wilcoxon Signed Rank (WSR) test with a level of confidence 95%, for data analysis and interpretation. The results and findings of this study are reported in the following subsections.

5.2.2.1 Successful completion of tasks

We noticed that 60% of the participants (12 out of 20) completed all five drawing tasks on the first attempt without any error for both tools. On the other hand, the rest 40% of the participants (8 out of 20), made errors on both tools during the first attempt and later recovered the errors with minimal assistance and completed the drawing tasks. The majority of the participants realized an error when they were unable to close the path or unable to reach the expected starting peg. This aligns with the application of validation strategies

reported in Chapter 3. The participants also realized an error while they traversed through the entire drawing. For a few participants, the moderator explicitly mentioned that they had made an error when they could not recognize the error (for instance, missing sharp corners). For all self-identified and moderator-reported errors, all the participants were finally able to recover and complete the drawing tasks successfully with minimal assistance from the moderator. This minimal assistance primarily includes asking the participants to verify perpendicular, diagonal, straight, or parallel lines and the length of a straight line. As shown in Figure 5.26, we reported this information as the number of participants who succeeded with assistance (represented with red horizontal stripes). We also reported the number of participants who succeeded without assistance (represented with dotted green in Figure 5.26). Out of 100 drawing tasks (5 tasks x 20 participants) on each tool, the number of successful drawing tasks completed without assistance on Naamya (86, M = 4.3, SD = 1.13) is higher than on the pegboard-based drawing tool (81, M = 4.05, SD = 1.39). However, according to the WSR test, there is no statistically significant difference (Z=-1.667, p=.096) between the number of tasks successfully completed without assistance on the drawing tools.

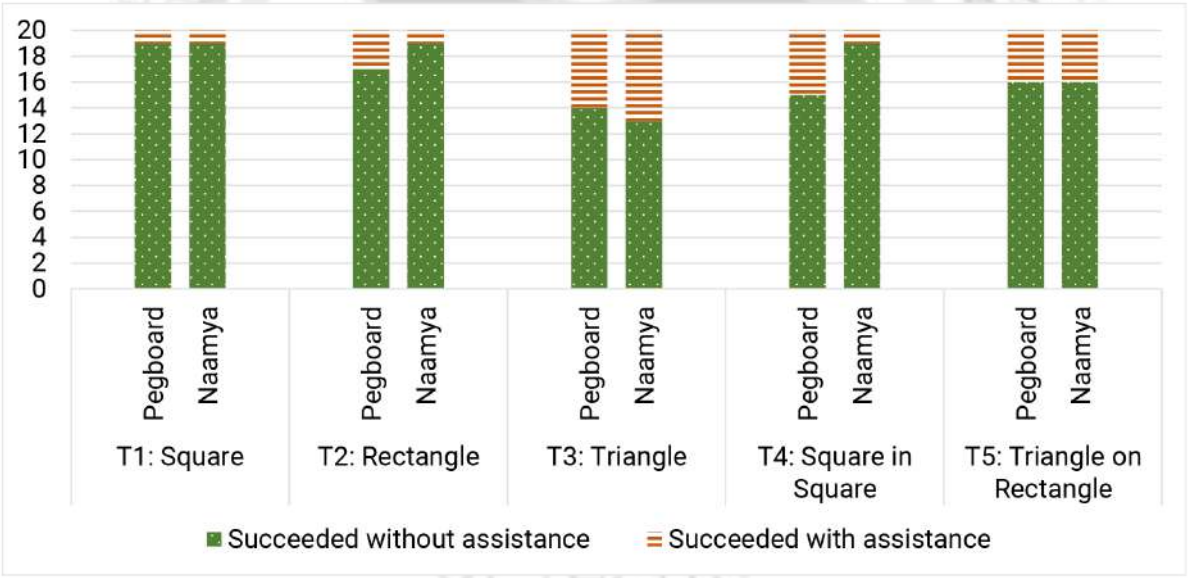


Figure 5.26: The number of participants who succeeded in the five drawing tasks without assistance (dotted green) and with assistance (red horizontal stripes) for both tools. Here Y-axis represents the number of participants. (Coloured Figure)

5.2.2.2 Number and types of errors

We also calculated the number of errors made by the participants on each tool. According to the WSR test, there is no statistically significant difference (Z=-1.667, p=.096) between the number of errors made by the participants on the drawing tools. However, as shown in Figure 5.27, for the majority of the drawing tasks except for drawing triangles (T3), the total number of errors on Naamya is either less than (T2 and T4) or equal (T1 and T5) to the number of errors on the pegboard-based drawing tool. To understand these errors in detail with respect to the drawing tools, we categorized all the recorded errors (14 on the digital tool and 19 on the pegboard) into two groups: slip and mistake (Norman, 1986). We have presented these two errors in Figure 5.27 for each drawing task and each drawing tool. As reported by Norman, 1986, a mistake is an error in the formation of an intention and a slip is an error in the execution of the intention. In the context of this study, a common example of slip is that the user-intended next hole to be used is correct; however, the user ends up making an error at the time of peg insertion. This slip often happens by selecting and inserting the peg in an unintended hole. In contrast, a mistake happens when the user-intended next hole to be used is incorrect. This incorrect intention is majorly a result of weak prior concepts or wrong counting of pegs. Similar slips and mistakes were also observed and reported in Chapter 3.

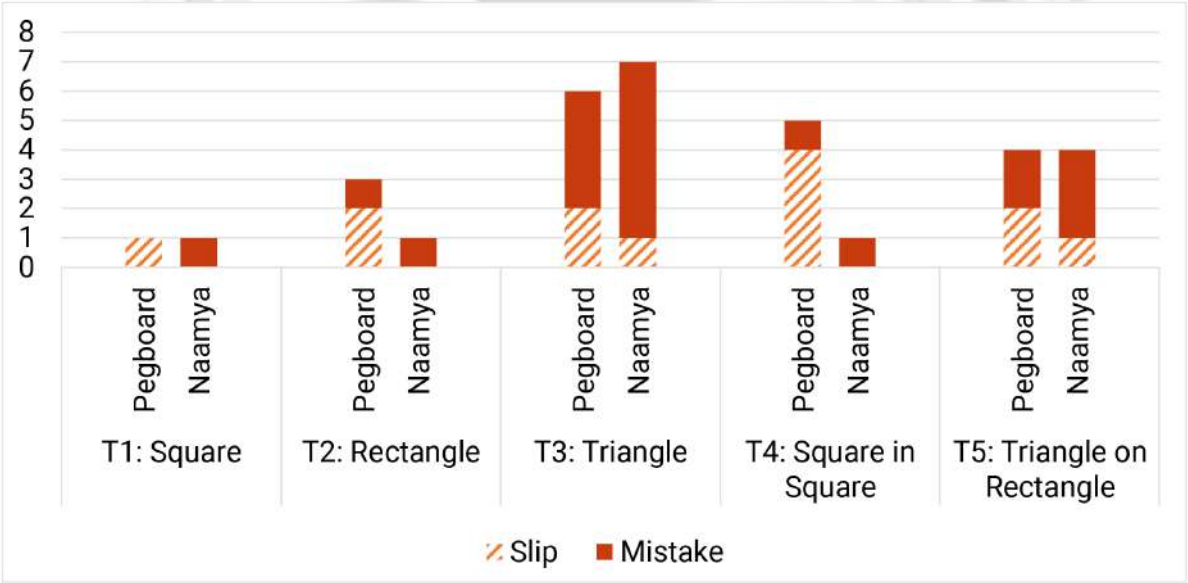


Figure 5.27: The total number of errors along the Y-axis (including both slips as orange diagonal stripes and mistakes as red solid fills), made for each task using each drawing tool. (Coloured Figure)

We found that considering both tools, the total number of mistakes (20 errors) is higher than the total number of slips (13 errors). However, according to the WSR test, there is no statistically significant difference (Z = -0.258, p = .796) between the number of slips and mistakes made by the participants. Similarly, according to the WSR test, there is no statistically significant difference between the number of slips and mistakes made by the participants on each tool, those are Naamya (Z = -1.930, p = .054) and Taylor Arithmetic Slate (Z = -0.520, p = .603). However, when the number of each type of error (slips or mistakes) is compared between the tools, we found statistically significant ($p < 0.05$) results. According to the WSR test, the number of slips made by the participants on Naamya is significantly lower (Z = -2.251, p = .024) than the number of slips on the pegboard-base drawing tool (Taylor Arithmetic Slate). In contrast, the number of mistakes made by the participants on Naamya is significantly higher (Z = -2.000, p = .046) than the number of mistakes on the pegboard-base drawing tool (Taylor Arithmetic Slate).

5.2.2.3 Analysis of the participants' Likert scale ratings and verbal responses

In figure 5.28, we present the mean of the participant's responses on a 7-point Likert scale for the ten statements (S1-S10). Since the collected data are not normally distributed, we used the Wilcoxon Signed Rank (WSR) test to compare the participants' ratings. We found that between Naamya and the pegboard-based drawing tool (Taylor Arithmetic Slate), there is no statistically significant difference in terms of "S1: Easy to use" (Z = -1.633, p = 0.102), "S2: Easy to learn" (Z = -1.732, p = 0.083) and "S10: Easy to build a mental spatial layout" (Z = -1.604, p = 0.109). However, we found that Naamya is significantly more "S3: Encourages to continue practising drawing" (Z = -3.827, p = 0.0001), "S4: Confidence offering in correctly drawing straight lines" (Z = -4.179, p = 0.00002), "S5: Confidence offering in selecting the next intended hole correctly" (Z = -4.179, p = 0.00002), "S6: Easy to perceive the change in the direction of progress" (Z = -3.035, p = 0.002), and "S7: Error-proof to the wrong next-hole selection" (Z = -4.127, p = 0.00003). In terms of correct navigation from one hole to another, Naamya enables significantly more "S9: Enables correct navigation" (Z = -3.448, p = 0.001) as compared to the pegboard-based drawing tool (Taylor Arithmetic Slate). On the other hand, in terms of ease of navigation, the pegboard-based drawing tool (Taylor Arithmetic Slate) offers significantly higher "S8: Easy to navigate" (Z = -3.166, p = 0.002).

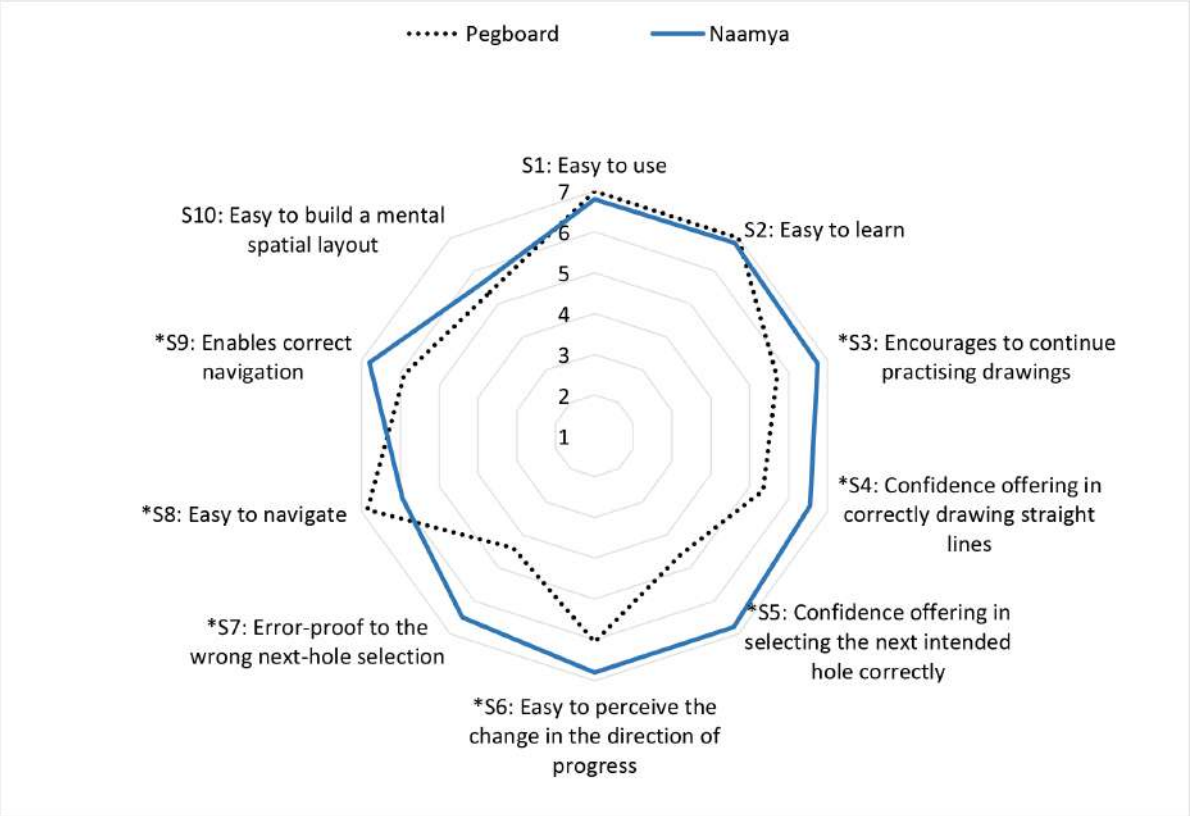


Figure 5.28: Comparison of the tools based on the participants' ratings on the 7-point Likert Scale for ten statements (1-strongly disagree and 7-strongly agree). Here statements preceding with an asterisk (*S3-*S9) represent statements for which a statistically significant difference was found using the WSR test. In this figure, the blue solid line represents Naamya and the black dotted line represents the pegboard-based drawing tool (Taylor Arithmetic Slate). (Coloured Figure)

We also recorded and analysed the users' confidence during drawing, preferences for using one of the tools, and requirements for further training on these tools. As shown in Figure 5.29, the majority of the participants (75% that is 15 out of 20) preferred to use Naamya. While one participant preferred to use the pegboard-based tool Taylor Arithmetic Slate, the rest four reported no preferences. All participants reported confidence in correctly drawing a straight line, selecting the next hole, and changing direction using Naamya. Regarding the need for additional training, the majority of the participants reported that they did not require further training. Here, 70% of the participants reported that Naamya required no further training, while 100% of the participants reported the same for Taylor Arithmetic Slate.

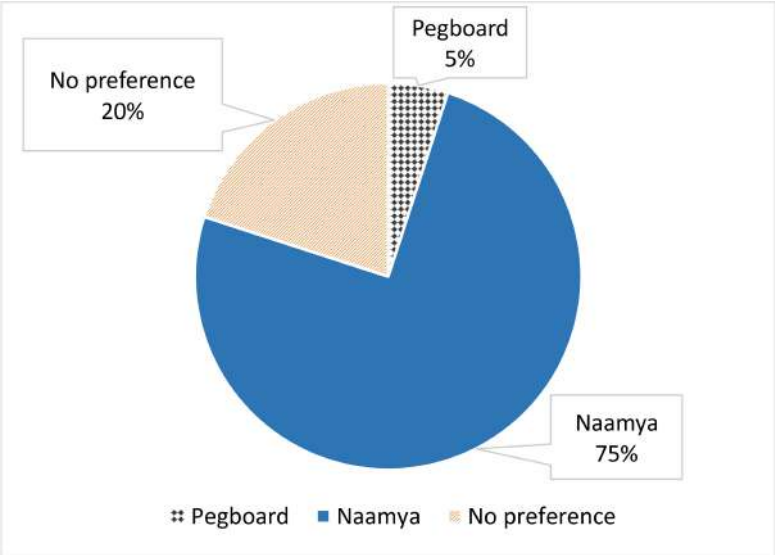


Figure 5.29: Pie chart presenting participants' preferences for the drawing tools. Here the blue solid fill region represents preferences for Naamya, the black solid diamond grid region represents preferences for the pegboard-based drawing tool (Taylor Arithmetic Slate), and the region with orange diagonal stripes represents the participants who reported no preferences. (Coloured Figure)

5.2.3 Discussion

We analyzed the results obtained for the number of successfully completed tasks with and without assistance, errors during drawing on each tool for each task, and participants' ratings on a 7-point Likert scale for the ten statements (S1-S10). The results of the WSR test show that there is not enough evidence to reject the null hypothesis that there is no significant difference between the tools in terms of the number of successful completion of tasks and errors. This indicates that with limited training and with a subset of the proposed functions (Table 5.3) Naamya is found to be as effective as the extensively used existing pegboard-based tool (Taylor Arithmetic Slate).

Analyzing the total number of errors for each task on each drawing tool (Figure 5.27), we observed that the number of errors on Naamya is either less than (for T2 and T4) or equal (for T1 and T5) to the number of errors on the Taylor Arithmetic Slate, except for the third task (T3) of drawing a triangle. According to the participants, drawing squares and rectangles is easier on both tools than drawing triangles. In this context, one participant mentioned, "For squares and

rectangles, I need to count only one or two edges since opposite edges are of the same length and adjacent edges are always perpendicular, which is not difficult. But for triangles, it may be different". Similar difficulties in drawing and visualizing the triangles were also identified and reported in the literature (Grussenmeyer & Folmer, 2016). We observed that participants often validate the shape or progress in drawing the shape, particularly while drawing a triangle. This aligns with the findings reported in Chapter 3, where participants applied several strategies to correctly draw the top edges of triangles. For pegboard-based drawing, the participants validated the shape or progress in drawing the shape by touching with fingers and palms. In contrast, while using Naamya, participants often verified the drawing by traversing it at the end of completing the drawing or in case they could not complete it correctly. The participants avoided validating the progress in drawing due to the need for sequential traversal. We believe not validating the progress in the drawing has led to more errors in the case of drawing triangles on Naamya. To avoid traversing the drawing, one participant drew the top edges of the triangle in task T3 by inserting one digital peg at a time on each edge. This technique is similar to the strategy named continuous validation of vertices reported in Chapter 3. In this context, the use of the smart functions proposed in Chapter 3 could be beneficial to guide the users to validate the progress in drawing without traversing it.

For tasks T3 and T5, although both have triangles, we observed that in the case of T5, providing the tactile card (Figure 5.23a) helped the participants to complete the task successfully. While participants were trying to complete task T5 after reading the tactile card, we observed that the participants were more focused on replicating the peg count rather than understanding and replicating the compound shape of task T5. In this context, one participant mentioned how many pegs would be required to complete the triangle after completing the rectangle of task T5. In contrast, for drawing task T3, where no tactile card was provided for drawing the triangle, participants had to rely on their prior knowledge and experience of drawing a triangle which led to more errors. In this context, one participant who was trying to draw an isosceles triangle mentioned, "I want to make the triangle's left and right edges equal in length. But I don't know how many pegs will be needed on them to make them both equal in length and also to meet at a common vertex.". Similar difficulties in drawing triangles have also been observed and reported in Chapter 3. Similarly, analyzing the types of errors for each task on each drawing tool (Figure 5.27), we observed that the

number of mistakes is higher than slips for task T3 on both tools. This higher number of mistakes indicates the error during the formation of intention, which relies on prior knowledge and experience in drawing. This also aligns with the difficulty reported by the participants in drawing triangles on both tools without using tactile cards.

The number of errors for tasks T4 and T5 (Figure 5.27) indicates that although both the tasks require drawing compound shapes after reading the tactile cards (Figure 5.23), the number of errors for T4 on pegboard and for T5 on both tools are higher. As discussed earlier, the number of errors for task T5 is majorly associated with weak prior knowledge of drawing triangles which eventually led to difficulty in drawing and a higher number of errors on both tools. The number of errors for task T4 (drawing a square inside another square) on Naamya was lower than the pegboard-based drawing tool (Figure 5.27). Although participants reported that drawing squares and rectangles is easier on both tools, we observed that closely placing the physical pegs on the Taylor Arithmetic Slate contributed to the errors. Participants were often confused by the edge of the outer square considering it to be the edge of the inner square. Participants also missed inserting pegs in crowded zones where the edges of the outer and the inner squares are required to be drawn next to each other without leaving any empty holes between them. However, in the case of the bend gesture-based digital drawing tool (Naamya), placing the pegs close to each other was not a challenge as the participants didn't have to explore and select the target grid positions by touching.

In terms of the number of errors, we found no significant difference between the tools. On the other hand, according to the WSR test, the number of slips made by the participants on Naamya is significantly lower than the same on the Taylor Arithmetic Slate. One of the major slips on the pegboard-based drawing tool is due to the selection of the wrong hole. A wrong perception of direction usually causes this. On the other hand, the bend gesture-based interaction on Naamya enables users to have more control over navigation due to bend gestures' inherent spatial directional cues. In this context, one participant mentioned, "It is easy to feel the direction of movement while performing a bend gesture. I feel more confident that I will not end up in an unintended grid position. Moreover, the audio description adds another level of confirmation to strengthen my confidence". With a significantly lower number of slips during drawing enables us to believe that the use of Naamya for an extended period of time with advanced and smart features could offer better performance. In contrast, the

number of mistakes made by the participants on Naamya is significantly higher than the same on Taylor Arithmetic Slate. We observed that the majority of the mistakes were due to weak prior concepts regarding the shape or wrong counting of pegs. In particular, the weak prior concept regarding drawing a triangle in different ways has a major contribution to these errors. Similar observations were also identified and reported in Chapter 3. However, we believe that the lack of simultaneous validation while the drawing was in progress also contributed towards the higher number of mistakes by creating confusion regarding counting, as no students have prior knowledge of using row and column numbers to refer to the grid positions during drawing. Such wrong counting resulted in making wrong decisions by the participants during drawing. We believe the further practice of using such counting presented as row and column numbers could help users reduce the number of mistakes. In addition, the use of the smart functions proposed in Chapter 3 could also assist users in avoiding mistakes.

We also analyzed the statistical findings obtained for the participants' ratings on a 7-point Likert Scale for the ten statements (S1-S10). We found no statistically significant difference between Naamya and Taylor Arithmetic Slate for ease of using (statement S1 in Figure 5.28) and ease of learning (statement S2 in Figure 5.28) the tools. This agrees with the majority reported no requirement for further training on both tools. It was also observed that the participants were able to relate their experience of drawing on the pegboard-based drawing tools to the drawing process of Naamya. In this context, one participant mentioned. "I think both tools work in the same way, but one uses real pegs that we move by hands, and the other uses digital pegs that we move by bending Naamya". Referring to the grid-based drawing approach, one participant mentioned, "It is easy to learn and draw on Naamya by following the row and column numbers mentioned in the audio description without counting them in my mind". A similar advantage of using a grid-based metaphor on learnability was reported in the literature for keypad-based drawing (Kamel & Landay, 1999). Referring to bend gesture-based interaction, one participant mentioned, "I enjoyed using Naamya. I can bend this phone and easily draw shapes. I can easily learn to use this flexible phone to operate other Apps without assistance". This indicates the ease of using and learning the interaction modality, which also helped the participants to draw shapes using Naamya. The participants also enjoyed that they could bend the digital device. This also aligns with the existing literature where bend gestures were found to be easy to learn and perform by users with

blindness (Ernst et al., 2017) and comfortable to use (Ernst & Girouard, 2016a).

According to the participants' 7-point Likert Scale ratings, the use of Naamya is significantly more encouraging to continue practising drawings than the Taylor Arithmetic Slate (statement S3 in Figure 5.28). In this context, one participant referring to the process of drawing on Naamya mentioned, "It (the FOCUS) is like a ball on a plate which I can push in a direction by bending the corners, and the speaker tells me where the ball goes". Similar amusement perceived during drawing was also reported in the literature (Grussenmeyer & Folmer, 2016). Referring to the inherent tactile feedback of bend gestures, one participant mentioned, "I don't have to worry whether I have provided the input or not. When I bend the tool, I am sure that I am doing it right. The vibration and the beep also helped me to confirm that the input is already provided". Similar advantages of bend gestures due to their innate tactile and kinesthetic feedback have also been reported in the literature (Wightman et al., 2011). The bipolar nature of the bend gestures selected for the "Insert Peg" and "Remove Peg" functions helped users relate to the metaphor of physically inserting and removing a peg. In this context, one participant mentioned, "This is similar to how I push and pull a board pin using both hands". Similar observations regarding bipolar bend gestures were also reported in the literature (Ahmaniemi et al., 2014). Referring to the ease of perceiving the spatial information and the reason for using Naamya, another participant mentioned, "Using Naamya, I can remember and easily describe the shapes and their positions. Since my drawing is saved, I can later read it and modify it further". This aligns with the findings in literature (Balik et al., 2014) where participants reported similar ease of remembering diagrams. However, investigating the effect on memory is beyond the scope of this research. We believe this bend gesture-based drawing process using all the functions of Nammya has the potential to be used as a drawing tool for academic, professional, and leisure activities. With this novel bend gesture-based input modality with inherent tactile feedback and directional cues accompanied by the selected external feedback modalities, Naamya can also be used as an interactive tool for collaborative drawing and peer learning.

According to the participants' 7-point Likert Scale ratings, the use of Naamya is significantly more confidence offering in correctly drawing straight lines (statement S4 in Figure 5.28) and more confidence offering in selecting the next intended hole correctly (statement S5 in Figure 5.28). We also found that while drawing on Naamya, it is

significantly easier to perceive the change in the direction of progress as compared to Taylor Arithmetic Slate (statement S6 in Figure 5.28). This also aligns with the previous finding that the number of slips made by the participants while drawing on Naamya is significantly lower than the same on the Taylor Arithmetic Slate. We also observed (during this study and the previous study reported in Section 3.2) that the slips on the Taylor Arithmetic Slate are often due to inserting the pegs in the wrong holes, although the intended holes were correct. Such slips often lead to failures in completing intended straight lines correctly. In this context, one participant mentioned, "On this tool (Naamya), I am sure that I am moving in the direction I want to". Another participant, while drawing on the pegboard, mentioned, "I thought I was drawing a straight line, but somewhere in the middle, I shifted". The higher confidence during drawing on Naamya was accomplished by the ease of perceiving and executing the intended change in the direction of progress. Unlike the Taylor Arithmetic Slate, Naamya offers distinct bend gestures to navigate in one of the eight cardinal directions. This indicates that the association of the selected bend gestures of Naamya with appropriate spatial directional cues allowed the participants to easily and correctly perceive and execute the change in the direction of progress. The advantages of selecting bend gestures associated with appropriate spatial directional cues were also reported in the literature (Ahmaniemi et al., 2014; Borah, Seth, & Sorathia, 2021). In this context, one participant mentioned, "When I bend the flexible phone, I already knew in which direction the FOCUS will move". Another participant mentioned, "I want to continue using Naamya in the future as I feel more confident in moving the FOCUS. I know I will not move towards a direction until I bend the device towards that direction". This reported higher confidence and ease of perceiving the change in direction also contributed to the aforementioned higher encouragement to continue drawing on Naamya.

According to the participants' 7-point Likert Scale ratings, drawing on Naamya is significantly more error-proof to the wrong next-hole selection as compared to Taylor Arithmetic Slate (statement S7 in Figure 5.28). This indicates a major advantage of using Naamya over the pegboard-based tool (Taylor Arithmetic Slate). We observed that wrong hole selection happens both intentionally and unintentionally. The intentional wrong hole selection is most commonly due to the wrong prior concept of geometric drawing or wrong counting. In comparison, unintentional wrong hole selection is most commonly a slip (type

of error). We observed that on the Taylor Arithmetic Slate, these slips usually occur while users manually pick up and try to insert the pegs into the holes or due to an unknown rotation of the drawing board while drawing. In contrast, these challenges do not arise when using Naamya. This also aligns with the significantly smaller number of slips made by the participants on Naamya as compared to the Taylor Arithmetic Slate. The directional cues associated with the selected bend gestures of Naamya also helped the participants to prevent wrong next-hole selection errors. In this context, one participant mentioned, "I am confident that I will never select a wrong hole which I didn't intend to while drawing on Naamya. I know in which direction I want to move, and accordingly, I will bend the tool". The participant also mentioned the positive contribution of the provided audio descriptions that clearly indicate the grid position (row and column numbers) during drawings. Referring to this assistance provided by the audio description containing row number and column number, another participant mentioned, "If I correctly know the peg counts to draw a shape, I will not make any error on Naamya". Such a grid-based drawing approach accompanied by audio feedback was also found to be effective in the literature (Kamel & Landay, 1999, 2002b).

According to the participants' 7-point Likert Scale ratings, while drawing on the Taylor Arithmetic Slate, it is significantly easier to navigate from one hole to another as compared to Naamya (statement S8 in Figure 5.28). In contrast, according to the participants, while drawing on Naamya, it enables significantly more correct navigation as compared to Taylor Arithmetic Slate (statement S9 in Figure 5.28). Although Naamya enables users to navigate correctly, the ease of navigation is higher in the case of the physical pegboard-based tool due to the freedom of quickly navigating the grid by moving the fingers and hands. However, we noticed that this freedom of navigation has a negative impact where the unrestricted movements of hands and fingers overwhelm the infrequent users of pegboards with several tactile stimuli. This could also result in increased confusion and error during navigation on the Taylor Arithmetic Slate and eventually reduced confidence during drawing tasks. In this context, while drawing on Taylor Arithmetic Slate, one participant mentioned, "I often do not remove my finger (left-hand index finger) from the end (the progressing end of the pegboard-based drawing) until it is complete. Otherwise, I might get lost or lose track of what I am doing, and I have to check the drawing from the beginning". We observed similar challenges during the previous study on pegboard-based drawing reported in Section 3.2. We

observed that participants were able to quickly perceive and remember the mappings between the bend gestures and the functions. The similarity between the spatial directional cues associated with the bend gestures and the direction of the navigation functions enabled the participants to correctly navigate while drawing on Naamya without paying much attention. In this context, one participant mentioned, "As I can move in a direction by bending the device towards that direction, I will not move to a wrong direction by mistake". Referring to potential slips on the Taylor Arithmetic Slate, the same participant mentioned, "I might make errors on the pegboard. When I explore the surrounding holes, they all feel the same except in which direction I move my finger to discover the holes. So I have to be careful before selecting the next hole for peg insertion". We also observed that a few participants were performing the Top-side Bend-downward Small-size gesture to navigate towards the top instead of the Bottom-side Bend-upward Small-size gesture. Although this gesture was not introduced during training, the participants found it intuitive to trigger the "Navigate Towards Top" function with this Top-side Bend-downward Small-size gesture. This also indicates the intuitiveness of bipolar bend gestures reported in the literature (Ahmaniemi et al., 2014; Borah, Seth, & Sorathia, 2021).

We found no statistically significant difference between Naamya and Taylor Arithmetic Slate for ease of building a mental spatial layout (statement S10 in Figure 5.28). Although we found no statistically significant difference, according to the participants' verbal responses, the spatial directions associated with bend gestures enabled them to relate the shapes with each other spatially. In this context, one participant mentioned, "Now I have to draw a triangle above this rectangle by moving the FOCUS upward". However, for these tasks, tactile cards were provided, which also contributed towards comprehending spatial information. Referring to the ease of perceiving the spatial information, another participant mentioned, "Using Naamya, I can remember and easily describe the shapes and their positions". We also noticed that during drawing, participants were referring to different regions of the shapes by using egocentric coordinate representations irrespective of the current hole in FOCUS. For instance, "left corner", "right corner", "top corner", and "bottom edge", to name a few. However, to refer to their next step in drawing using these egocentric coordinate representations, they used these representations in relation to the current hole in FOCUS. For instance, one participant mentioned, "I have to insert a peg in the left hole (with

respect to the current hole in FOCUS) to draw the edge (right edge of the triangle lying above the rectangle)". However, investigating the effect of this bend gesture-based drawing tool (Naamya) on spatial cognition is beyond the scope of this research. We believe, Naamya has the potential to convey the necessary spatial information for creating a mental spatial layout of the drawings, and the proposed smart features could further augment Naamya's capability in this regard.

5.3 Summary

This chapter reported the two studies of Phase III (Study 5 and Study 6). The first study reported in this chapter (Study 5 reported in Section 5.1) detailed the design of the bend gesture-based drawing tool (Naamya) by involving students with visual impairment or blindness and their teachers in the design process. This participatory design study was completed in two phases. The first phase of the participatory design study (reported in Section 5.1) finalised the required feedback modalities of Naamya. The second phase of the participatory design study (reported in Section 5.1) finalised the tool's basic and advanced functions. This phase also identified the mappings between the functions with bend gestures and gesture completion strategies. The findings of this participatory design study answer the fourth research question (RQ 4 reported in Section 1.2). The second study reported in this chapter (Study 6 reported in Section 5.2) details the user study that evaluated the effectiveness of using Naamya for creating simple and compound primitive geometric shapes as compared to a pegboard-based tool (Taylor Arithmetic Slate). The findings of this study answer the fifth research question (RQ 5 reported in Section 1.2). In the next chapter (Chapter 6), we present and discuss this thesis work's four major contributions and implications.

Chapter 6

Discussion on Contributions and Implications

The previous chapter (Chapter 5) presented two studies, including the design of Naamya through a participatory approach and evaluation of Naamya. Overall this thesis work laid out four major contributions. This chapter presents and discusses this thesis work's contributions and implications.

6.1 Discussion on Contributions and Implications

In this thesis work, we designed a digital drawing tool that corresponds to the user's mental model of using existing tactile pegboard-based drawing tools in which bend gestures are the primary input modality. The inherent tactile and kinesthetic feedback of bend gestures and their association with spatial directional cues motivated us to select and investigate bend gestures in detail as the primary input modality. In this work, we conducted six studies divided into three phases. In the first phase (first and second studies reported in Chapter 3), we investigated the use of existing drawing tools. In the second phase (third and fourth studies reported in Chapter 4), we investigated the bend gesture-based input modality. Finally, in the third phase (fifth and sixth studies reported in Chapter 5), we designed and evaluated the bend gesture-based drawing tool Naamya. This thesis work laid out four major contributions, which were briefly reported in the first chapter of this thesis. In the following subsections, these four major contributions are discussed in detail with their implications.

1. The first major contribution of this thesis is the findings and analysis of user research on geometric drawings by students with blindness or low vision in India. These findings include the following - academic challenges and suggested reforms, limited features of current drawing tools and scope for improvement, and scope for improvement through technological intervention (presented in Section 3.1 of Chapter 3) and drawing patterns, strategies used for drawing and reading primitive geometric shapes (triangles and rectangles), errors in drawing and reading shapes, and a set of functions to design a digital drawing tool that corresponds to the user's mental model of using existing drawing tools (presented in Section 3.2 of Chapter 3).

   While there was limited information in the existing literature from the perspective of Indian students and teachers regarding the use of existing tactile drawing tools, the findings reported in Section 3.1 such as academic challenges and suggested reforms regarding mathematical drawing, limited features of current drawing tools and scope for improvement, and scope for improvement through technological intervention will bridge this gap. In particular, these findings will help academicians and policymakers to incorporate essential steps regarding the use of drawing tools into the curriculum keeping the users' current experience in mind. In addition, these findings will also help Human-computer Interaction (HCI) researchers and User Experience (UX) designers working in the area of accessibility, assistive tools, and learning tools to guide their research works and design decisions.

   The drawing patterns, strategies used for drawing and reading primitive geometric shapes (triangles and rectangles), and the errors in drawing and reading shapes reported in Section 3.2 will also help HCI researchers and UX designers working in the area of accessibility, assistive tools, and learning tools to gain an in-depth understanding of the tactile drawing process.These findings will also help them to design digital drawing tools for users with blindness or low vision keeping their mental model of using existing tools at the center of the design process. In addition, the reported set of functions derived from the findings of this study could be directly implemented on any digital platform to develop a digital drawing tool for users with blindness or low vision. The advanced and smart functions reported in Chapter 3 could help redesign existing digital drawing tools to help experienced users draw simple and

compound geometric shapes with reduced effort and time.

2. The second major contribution of this thesis is the set of recommendations to design bend gesture-based interactions with basic and additional descriptors of bend gestures considering the performance and preference of users with blindness or low vision. As reported in Section 4.1 of Chapter 4, these recommendations include the following - use of size-based gestures with two magnitude levels where size is an additional descriptor, use of two magnitude levels of size at all corners, use of one magnitude level of size for both sides, use of both directions of bend for BLV users, use of small magnitude level of angle in implementing a threshold-based strategy to provide discrete input, use of large magnitude level of angle as the extreme angle required for continuous input.

   The results and findings on user performance and preference for two additional descriptors of bend gestures reported in Section 4.1, will add to the existing literature on bend gesture-based interaction by bridging the gap concerning their use with two magnitude levels of size and angle of bend on smartphone-sized flexible devices. These findings on user performance and preference will help HCI researchers and UX designers working in the area of deformable user interfaces, smartphone-sized flexible handheld devices, and accessible bend gesture-based interaction. The design recommendations reported in Section 4.1 will also be helpful for HCI researchers and designers to design bend gesture-based interactions. For instance, based on user performance and preference, frequently used functions could be mapped to bend gestures at easy-to-perform locations and directions and with one or two magnitude levels of additional descriptors which are easy to perform and differentiate. Moreover, the confidence intervals identified for two magnitude levels of size and angle of bend could be used as thresholds to recognize these gestures on a flexible device with similar rigidity.

3. The third major contribution of this thesis is the set of bend gesture completion strategies that can be utilized while designing for users with blindness or low vision. As reported in Section 4.2 of Chapter 4, the gesture completion strategies for discrete input are On-Hold, On-Release, On-Relax, and On-Double-Bend and the gesture completion strategies for continuous input are On-Hold, On-Second-Bend, and

On-Quick-Relax.

The results and findings of these user-defined bend gesture completion strategies reported in Section 4.2 will add to the existing literature on bend gesture-based interaction by providing opportunities to utilize them in different contexts. For instance, the On-Hold strategy could be implemented to provide input with higher confidence. The findings and design recommendations will help HCI researchers and UX designers working with deformable user interfaces and smartphone-sized flexible handheld devices to utilize a limited set of bend gestures for mapping with different functions. For instance, the same bend gesture could be mapped to different functions by selecting different gesture completion strategies or different hold times for the same On-Hold strategy.

4. The fourth major contribution of this thesis is the bend gesture-based smartphone-sized flexible handheld digital tool (Naamya) for drawing primitive geometric shapes that corresponds to the user's mental model of using existing tactile pegboard-based drawing tools (presented in Section 5.1 of Chapter 5). Users provide input on Naamya by bending the device to trigger the associated functions. The objective behind investigating the use of bend gestures for drawing primitive geometric shapes is to overcome the limitations of analogue drawing tools and input modalities that do not offer both tactile feedback and association with spatial directions. In this context, we found that the bend gesture-based digital drawing tool (Naamya) and the pegboard-based drawing tool (Taylor Arithmetic Slate) are equally effective in drawing primitive geometric shapes containing straight lines. Naamya also leads to significantly less number of slips during drawing. Most notably, the perceived inherent tactile and kinesthetic feedback of bend gestures and the spatial directions associated with the bend gestures offer several advantages to Naamya. Naamya encourages to continue practising drawings, offers confidence in correctly drawing straight lines, offers confidence in selecting the next intended hole correctly, offers ease of perceiving the change in the direction of progress, makes the drawing task error-proof to the wrong next-hole selection, and enables correct navigation. We also found no statistically significant difference between the tools in terms of ease of use, ease of learning, and ease of building a mental spatial layout.

The results and findings of the evaluation of Naamya, the bend gesture-based digital drawing tool reported in Section 5.2 of Chapter 5, will add to the existing literature on digital drawing tools for visually impaired and blind users with the evidence that it is as effective as the extensively used pegboard-based drawing tool, Taylor Arithmetic Slate, in drawing primitive geometric shapes containing straight lines. It also contributes to the existing literature on bend gesture-based interaction by bridging the gap of investigating the potential of bend gestures as the primary input modality of a digital drawing tool for individuals with blindness or low vision for the effective drawing of primitive geometric shapes. From the perspective of Information and Communication Technologies for Development (ICT4D), the proposed bend gesture-based digital drawing tool, Naamya itself, contributes to the use of digital tools and technologies for education by users with blindness or low vision. Users with blindness or low vision can also utilize this tool for collaborative drawing tasks with others. Moreover, the process of finalising the bend gestures and the gesture completion strategies for the functions of the drawing tool could also help HCI researchers and UX designers to apply the same in a different context. Furthermore, the mapped bend gestures and the design decisions associated with these mappings could be extended and advanced by HCI researchers and UX designers to design advanced versions of this drawing tool or transfer this knowledge to similar applications, such as drawing graphs and reading maps, to name a few. These findings will also help researchers and designers working in the area of tangible user interfaces to design and develop tangible digital drawing tools for users with blindness or low vision. Moreover, we reported the fabrication process of functional smartphone-sized flexible prototypes (in Chapter 4 and Chapter 5) with flexible 3D-printed internal structures embedded inside silicone casts to produce varying flexibility zones on the prototype's surface. HCI researchers and UX designers of deformable user interfaces could adopt this proposed fabrication process along with the same or modified flexible 3D-printed internal structure for designing and investigating bend gesture-based interaction.

In addition to the core contributions detailed in this thesis, the findings of the studies reported in this work seek to highlight the importance of inclusive education through technological interventions to facilitate a better understanding of mathematical drawings

among students with blindness or low vision. One important factor contributing to students with visual impairment and blindness dropping out of school early is their difficulties in learning mathematical concepts. By enhancing their mathematical competencies, we can pave the way for more inclusive educational and career opportunities in Science, Technology, Engineering, and Mathematics (STEM). This is critical for both individual empowerment and the advancement of society. Enhancing the quality of and access to mathematics education for students with visual impairment and blindness will serve as a cornerstone in reducing dropout rates and fostering a more inclusive academic environment. The integration of tools like this digital drawing tool (Naamya) into educational frameworks can revolutionise the learning experience for these students, making visually demanding mathematical concepts more accessible and comprehensible. Such advancements will not only aid in academic pursuits but also empower these individuals with essential life skills, enabling them to contribute to the world more effectively.

6.2 Summary

This chapter presented and discussed the four major contributions of this thesis work and their implications. The first major contribution of this thesis is the findings and analysis of user research on geometric drawings by students with blindness or low vision in India. The second major contribution of this thesis is the set of recommendations to design bend gesture-based interaction with basic and additional descriptors of bend gestures considering the performance and preference of users with blindness or low vision. The third major contribution of this thesis is the set of bend gesture completion strategies that can be utilized while designing for users with blindness or low vision. The fourth major contribution of this thesis is the bend gesture-based smartphone-sized flexible handheld digital tool (Naamya) for drawing primitive geometric shapes that corresponds to the user's mental model of using existing tactile pegboard-based drawing tools. In the next chapter (Chapter 7), we present the concluding remarks on this research work and mention the limitations and future scopes.

Chapter 7

Conclusion, Limitations and Future Scopes

The previous chapter (Chapter 6) discussed the four major contributions of this thesis along with their implications. In this chapter, we have presented the concluding remarks on the thesis and mentioned the limitations and future scopes of this research work.

7.1 Conclusion

In the Indian context, students with blindness or low vision practice mathematical drawings on tactile tools as learning aids, such as geoboards, raised-line drawing boards, and pegboards. This tactile drawing process is time-consuming and becomes challenging for complex diagrams. These tactile drawing tools also have limitations in creating, storing, erasing, and modifying the drawings. In this context, this thesis aimed to design a digital drawing tool with an input modality that provides innate tactile feedback to users during the interaction. Considering the inherent tactile and kinesthetic feedback of bend gestures and their association with spatial directional cues, this thesis investigated the potential of bend gestures as the primary input modality of a digital drawing tool for users with blindness or low vision. In this work, we selected smartphone-sized flexible handheld devices for designing the bend gesture space, considering smartphones to be the most commonly used and carried digital devices by blind users. We followed human-centered design approaches and conducted six studies in three phases (reported in Chapter 3, 4, and 5 respectively) where

each of these phases comprises two studies. Finally, we discuss the contributions of this thesis and their implications in Chapter 6.

The objective of the first phase was to understand the existing drawing tools and strategies used for drawing. In the first study of this phase, we conducted an interview-based retrospective study with students and teachers with blindness or low vision in the Indian context. This study aimed to understand the experience of students and teachers in learning and creating mathematical diagrams, the use of existing mathematical drawing tools, and the need and scope for improvement of drawing tools through technological interventions. The key findings of this study that helped our subsequent studies are that students usually learn only primitive geometric shapes at school. They often use different tools for learning shapes containing straight lines and circular paths. The pegboard-based tool (Taylor Arithmetic Slate) is the most commonly used drawing tool for primitive geometric shapes containing straight lines. We also found that students often take help from their sighted family members and friends during drawing and prefer digital tools with tactile and verbal feedback. In the second study of this phase, we conducted an observational study with students with blindness or low vision. This study aimed to understand the process of drawing primitive geometric shapes (triangles and rectangles) and reading compound shapes (containing a triangle and a rectangle) to help design digital drawing tools that correspond to the user's mental models of existing tools. We identified a set of validation strategies for drawing and shape identification techniques for reading which the participants used for error prevention and recovery. This understanding of the drawing and reading process, including the strategies, enabled us to propose the functions for designing a digital tool that corresponds to the user's mental model of using these pegboard-based drawing tools.

The objective of the second phase was to design the bend gesture space with additional descriptors and identify bend gesture completion strategies. In this phase, we conducted the first study to design the bend gesture space considering two basic descriptors (location and direction) and two additional descriptors (size and angle) of bend gestures. We conducted the second study of this phase to identify user-preferred gesture completion strategies that has the potential to overcome unwanted and unintended input. Considering the findings from the first phase, which evidence that blind and low vision (BLV) students often take help from the sighted, we included both BLV and sighted users during the two studies of this second phase.

The reason to include sighted users is the potential need to assist BLV users during teaching and training. The key findings of the first study of this phase that helped our subsequent studies are that both participant groups reported higher preferences for two magnitude levels of size and angle of bend at all four corners and for two magnitude levels of only size at the top and bottom sides of the device in portrait orientation. The BLV participants preferred both upward and downward bend directions, while the sighted participants preferred only upward. We also found that size-based gestures need less continuous attention and have reduced risk of potential error while bending the device. In addition, according to both participant groups, differentiation of two magnitude levels of size-based gestures is easier than angle differentiation and offers higher confidence during input. Later in the second study of this phase, we identified four (On-Hold, On-Release, On-Relax, and On-Double-Bend) and three (On-Hold, On-Second-Bend, and On-Quick-Relax) unique gesture completion strategies for discrete and continuous inputs, respectively. In addition, we found that the On-Hold gesture completion strategy for discrete input was preferred by the majority of the BLV participants as their first preference and the sighted participants as their second preference.

The objective of the third phase was to design the bend gesture-based digital drawing tool (Naamya) followed by its evaluation. We conducted the first study of this phase to design the bend gesture-based drawing tool through a participatory design approach. This study involved students with visual impairment or blindness and their teachers in the design process. In this participatory design study, we first finalised the required feedback modalities of the bend gesture-based drawing tool. In the next step of this participatory design study, we finalised the tool's basic and advanced functions and their mappings with bend gestures and gesture completion strategies. As the outcome of this first study (participatory design study) of this phase, a bend gesture-based smartphone-sized geometric shape drawing tool (Naamya) is designed. Finally, in the second study of this phase, we investigated the effectiveness of this bend gesture-based digital drawing tool (Naamya) compared to the pegboard-based drawing tool (Taylor Arithmetic Slate). We found no statistically significant difference between Naamya and Taylor Arithmetic Slate regarding effectiveness in drawing primitive geometric shapes containing straight lines. We also found that Naamya leads to significantly less number of slips during drawing. Most notably, the perceived inherent

tactile and kinesthetic feedback of bend gestures and the spatial directions associated with the bend gestures offer several advantages to Naamya. Naamya encourages to continue practising drawings, offers confidence in correctly drawing straight lines, offers confidence in selecting the next intended hole correctly, offers ease of perceiving the change in the direction of progress, makes the drawing task error-proof to the wrong next-hole selection, and enables correct navigation. In addition, we found no statistically significant difference between Naamya and Taylor Arithmetic Slate in terms of ease of use, ease of learning, and ease of building a mental spatial layout.

7.2 Limitations and Future Scopes

One of the major limitations of this bend gesture-based digital drawing tool (Naamya) is the exclusion of curved lines, especially circles, considering the users' habit of practising the circular shapes on separate geoboards or pegboards containing circular patterns rather than Taylor Arithmetic Slate due to the low resolution of its grid of holes. To address this limitation, further investigation is required with a high-resolution grid using the same tool with experienced users. This also indicates the scope for future research on designing similar bend gesture-based drawing tools to meet the user's mental model of drawing on circular geoboards or pegboards. Another scope for future research is on designing a similar bend gesture-based tool that combines the approaches of both rectangular and circular geoboards or pegboards. Another major limitation is the dimension of Naamya. This work's contributions are focused on smartphone-sized flexible devices in portrait mode. Since spatial directions are associated with bending the device locations (corners, sides, and axes), we believe changing the dimension or orientation of the device will not have an impact, provided the new shape of the flexible device is restricted to rectangular or square-shaped devices. Also, changing the dimension or changing the orientation of the device will not affect the functions of the drawing tool that corresponds to the user's mental model of using existing pegboard-based drawing tools. However, future research on the use of various rectangular and square-shaped flexible devices with different orientations could yield promising insights. Another limitation is the flexibility (or rigidity) of the prototype. We believe that modifying the prototype's flexibility would not have a major impact on the

selected gestures and gesture completion strategies, as long as the necessary affordances, such as lower rigidity along the bend lines in addition to grooves and markers on the surface of the device are provided to facilitate ease of performing the gestures.

The ease of perceiving the change in the direction of progress makes Naamya suitable for other applications such as graph drawing, coordinate geometry, and map navigation to name a few. Further research to investigate the application areas of Naamya with modified functions and feedback modalities could yield promising results. Moreover, further advancement of the current drawing tool with additional functions requires further investigation to finalise bend gestures and gesture completion strategies. In this context, using bend gestures for both discrete and continuous inputs requires further investigation to make the selected gesture space non-overlapping and non-ambiguous, which is outside the scope of this current research. The thresholds decided for prototyping are based on the results obtained from the reported sample. This offers the scope for future research on investigating the impact of age, gender, hand size, and other demographic distributions on finalising such hard thresholds. Another scope for future research is to investigate gesture recognition and rejection of unwanted input through fuzzy thresholds and machine learning techniques.

Considering the findings that students with blindness or low vision often take help from others during drawing, investigating Naamya for collaborative work with congenitally blind and late blind could yield promising results. Although the functions of Naamya and its bend gesture-based interactions could support both BLV and sighted user groups, the design and development of the application's graphical user interface is not this work's primary objective. The extension of Naamya to support collaborative work with sighted users accompanied by a graphical user interface requires further investigation. Through interviews with students and teachers, we are aware that the Taylor Arithmetic Slate is a commonly used tool across India. As a result, we believe that the findings of this research work are applicable in the Indian context although we have conducted all studies by physically visiting schools in the North Eastern Region of India. This also offers the scope for future research to compare Naamya with other drawing tools used by BLV students. Measuring the usability of a product primarily includes measuring effectiveness, efficiency, and satisfaction (Bevan, 2000). However, in this research, we have limited the investigation to effectiveness in drawing tasks. Furthermore, in this study, we used custom statements (reported in Section 5.2) in the questionnaire instead of

standard usability questionnaires to gain a thorough understanding of completing the drawing tasks using bend gestures. Moreover, further investigation is required to evaluate the usability of Naamya with all the proposed functions. Overall it indicates the scope for further evaluation of Naamya with users from different demographic distributions such as age, gender, percentage of visual impairment, age of blindness, and geographic location.

In this research work, we designed and evaluated a bend gesture-based digital drawing tool named Naamya for drawing primitive geometric shapes containing straight lines, such as squares, rectangles, and triangles. We evaluated the effectiveness of Naamya compared to the pegboard-based drawing tool (Taylor Arithmetic Slate) and found them equally effective in drawing simple and compound primitive geometric shapes containing straight lines. We also found that Naamya leads to significantly less number of slips during drawing. Most notably, the perceived inherent tactile and kinesthetic feedback of bend gestures and the spatial directions associated with the bend gestures offer several advantages to Naamya. Naamya encourages to continue practising drawings, offers confidence in correctly drawing straight lines, offers confidence in selecting the next intended hole correctly, offers ease of perceiving the change in the direction of progress, makes the drawing task error-proof to the wrong next-hole selection, and enables correct navigation. We also found no statistically significant difference between Naamya and Taylor Arithmetic Slate in terms of ease of use, ease of learning, and ease of building a mental spatial layout. In this chapter, we have presented the concluding remarks on the thesis and discussed this research work's limitations and future scopes. This thesis's contributions will help Human-computer Interaction (HCI) researchers and User Experience (UX) designers design digital drawing tools and bend gesture-based interactions for users with blindness or low vision.

References

Abras, C., Maloney-Krichmar, D., & Preece, J. (2004). User-centered design. *Bainbridge, W. Encyclopedia of Human-Computer Interaction. Thousand Oaks: Sage Publications*, *37*(4), 445–456.

Ahmaniemi, T. T., Kildal, J., & Haveri, M. (2014). What is a device bend gesture really good for? In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 3503–3512).

APH Collection. (2017). *Taylor arithmetic slate*. https://aphmuseum.org/record/taylor-arithmetic-slate/. (Last accessed on April 12, 2022)

Appelle, S., & Gravetter, F. (1985). Effect of modality-specific experience on visual and haptic judgment of orientation. *Perception*, *14*(6), 763–773.

Apte, V. S. (1965). *The practical sanskrit-english dictionary: containing appendices on sanskrit prosody and important literary and geographical names of ancient india*. Motilal Banarsidass Publ.

Arroba, P., Vallejo, J. C., Araujo, Á., Fraga, D., & Moya, J. M. (2011). A methodology for developing accessible mobile platforms over leading devices for visually impaired people. In *International workshop on ambient assisted living* (pp. 209–215).

Ashbrook, D., & Starner, T. (2010). Magic: a motion gesture design tool. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 2159–2168).

Azenkot, S., Ladner, R. E., & Wobbrock, J. O. (2011). Smartphone haptic feedback for nonvisual wayfinding. In *The proceedings of the 13th international acm sigaccess conference on computers and accessibility* (pp. 281–282).

Balik, S. P., Mealin, S. P., Stallmann, M. F., & Rodman, R. D. (2013). Gsk: universally accessible graph sketching. In *Proceeding of the 44th acm technical symposium on computer science education* (pp. 221–226).

Balik, S. P., Mealin, S. P., Stallmann, M. F., Rodman, R. D., Glatz, M. L., & Sigler, V. J. (2014). Including blind people in computing through access to graphs. In *Proceedings of the 16th international acm sigaccess conference on computers & accessibility* (pp. 91–98).

Bandyopadhyay, S., & Rathod, B. B. (2017). *The sound and feel of titrations: A smartphone aid for color-blind and visually impaired students.* ACS Publications.

Benko, H., Wilson, A. D., & Baudisch, P. (2006). Precise selection techniques for multi-touch screens. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 1263–1272).

Bevan, N. (2000). Iso and industry standards for user centred design. *Retrieved November*, *23*, 2010.

Blenkhorn, P., & Evans, D. G. (1998). Using speech and touch to enable blind people to access schematic diagrams. *Journal of Network and Computer Applications*, *21*(1), 17–29.

Boem, A., & Troiano, G. M. (2019). Non-rigid hci: A review of deformable interfaces and input. In *Proceedings of the 2019 on designing interactive systems conference* (pp. 885–906).

Borah, P. P., Panigrahi, A., & Sorathia, K. (2020). Tmove: Multimodal feedback actuator for non-visual exploration of virtual lines. In *Proceedings of the fourteenth international conference on tangible, embedded, and embodied interaction* (pp. 603–610).

Borah, P. P., Seth, J., & Sorathia, K. (2021). Gesture action mapping for deformation-based one-handed landscape mode interaction with flexible smartphone-sized devices. In *Proceedings of the twelfth indian conference on human-computer interaction* (pp. 1–10).

Borah, P. P., & Sorathia, K. (2019a). Direct observation of tactile geometric drawing by visually impaired and blind students. In *Proceedings of the tenth indian conference on human-computer interaction* (pp. 1–10).

Borah, P. P., & Sorathia, K. (2019b). Natural and intuitive deformation gestures for one-handed landscape mode interaction. In *Proceedings of the thirteenth international conference on tangible, embedded, and embodied interaction* (pp. 229–236).

Borah, P. P., Sorathia, K., & Sarcar, S. (2021). User-defined bend gesture completion strategies for discrete and continuous inputs. In *Ifip conference on human-computer interaction*

(pp. 192–202).

Borah, P. P., & Sorathia, K. B. (2022). Fabrication of nāmya: A bend and touch-sensitive flexible smartphone-sized prototype. *Human Behavior and Emerging Technologies*, *2022*.

Boring, S., Ledo, D., Chen, X., Marquardt, N., Tang, A., & Greenberg, S. (2012). The fat thumb: using the thumb's contact size for single-handed mobile interaction. In *Proceedings of the 14th international conference on human-computer interaction with mobile devices and services* (pp. 39–48).

Bornschein, J., Bornschein, D., & Weber, G. (2018). Comparing computer-based drawing methods for blind people with real-time tactile feedback. In *Proceedings of the 2018 chi conference on human factors in computing systems* (pp. 1–13).

Bornschein, J., & Weber, G. (2017). Digital drawing tools for blind users: A state-of-the-art and requirement analysis. In *Proceedings of the 10th international conference on pervasive technologies related to assistive environments* (pp. 21–28).

Bourne, R. R., Flaxman, S. R., Braithwaite, T., Cicinelli, M. V., Das, A., Jonas, J. B., … Limburg, H. (2017). Magnitude, temporal trends, and projections of the global prevalence of blindness and distance and near vision impairment: a systematic review and meta-analysis. *The Lancet Global Health*, *5*(9), e888–e897.

Boyd, L. H., Boyd, W. L., & Vanderheiden, G. C. (1990). The graphical user interface: Crisis, danger, and opportunity. *Journal of Visual Impairment & Blindness*, *84*(10), 496–502.

Brewster, S. A. (1994). *Providing a structured method for integrating non-speech audio into human-computer interfaces* (Unpublished doctoral dissertation). University of York.

Brewster, S. A., & Brown, L. M. (2004). Tactons: structured tactile messages for non-visual information display. In *Proceedings of the fifth conference on australasian user interface* (p. 15–23). Australian Computer Society.

Briotto Faustino, D., & Girouard, A. (2018a). Bend passwords on bendypass: A user authentication method for people with vision impairment. In *Proceedings of the 20th international acm sigaccess conference on computers and accessibility* (pp. 435–437).

Briotto Faustino, D., & Girouard, A. (2018b). Understanding authentication method use on mobile devices by people with vision impairment. In *Proceedings of the 20th international acm sigaccess conference on computers and accessibility* (pp. 217–228).

Brooks, M. (2009). Drawing, visualisation and young children's exploration of "big ideas". *International Journal of Science Education*, *31*(3), 319–341.

Brown, A., Pettifer, S., & Stevens, R. (2003). Evaluation of a non-visual molecule browser. *ACM SIGACCESS Accessibility And Computing*(77-78), 40–47.

Burstyn, J., Banerjee, A., & Vertegaal, R. (2013). Flexview: an evaluation of depth navigation on deformable mobile devices. In *Proceedings of the 7th international conference on tangible, embedded and embodied interaction* (pp. 193–200).

Byrd, N. (2014). Intuitive and reflective responses in philosophy. *University of Colorado*.

Calder, M., Cohen, R. F., Lanzoni, J., & Xu, Y. (2006). Plumb: an interface for users who are blind to display, create, and modify graphs. In *Proceedings of the 8th international acm sigaccess conference on computers and accessibility* (pp. 263–264).

Caporusso, N., Biasi, L., Cinquepalmi, G., Trotta, G. F., Brunetti, A., & Bevilacqua, V. (2017). A wearable device supporting multiple touch-and gesture-based languages for the deaf-blind. In *International conference on applied human factors and ergonomics* (pp. 32–41).

Cecchetto, S., & Lawson, R. (2015). Simultaneous sketching aids the haptic identification of raised line drawings. *Perception*, *44*(7), 743–754.

Census of India. (2011). *Census - 2011*. https://censusindia.gov.in. (Last accessed on January 10, 2022)

Chen, Y.-C., & Yeh, S.-L. (2008). Visual events modulated by sound in repetition blindness. *Psychonomic bulletin & review*, *15*(2), 404–408.

Cheung, V., Eady, A. K., & Girouard, A. (2017). Exploring eyes-free interaction with wrist-worn deformable materials. In *Proceedings of the eleventh international conference on tangible, embedded, and embodied interaction* (pp. 521–528).

Choi, S., & Kuchenbecker, K. J. (2012). Vibrotactile display: Perception, technology, and applications. *Proceedings of the IEEE*, *101*(9), 2093–2104.

Daliri, F., & Girouard, A. (2016). Visual feedforward guides for performing bend gestures on deformable prototypes. In *Graphics interface* (pp. 209–216).

Dey, S., Vidhya, Y., Bhushan, S., Neerukonda, M., & Prakash, A. (2019). Creating an accessible technology ecosystem for learning science and math: A case of visually impaired children in indian schools. In *Workshop on being (more) human in a digitised*

world, association of information systems – india chapter workshop, kolkata.

Dibeklioğlu, H., Hortas, M. O., Kosunen, I., Zuzánek, P., Salah, A. A., & Gevers, T. (2011). Design and implementation of an affect-responsive interactive photo frame. *Journal on multimodal user interfaces*, *4*(2), 81–95.

Directorate General of Health Services. (2020). *Dghs newsletter*. https://dghs.gov.in/WriteReadData/userfiles/file/DGHS%20Newsletter10.pdf. (Last accessed on April 15, 2021)

Dulin, D. (2007). Effects of the use of raised line drawings on blind people's cognition. *European journal of special needs education*, *22*(3), 341–353.

Ebefors, T., Kälvesten, E., & Stemme, G. (1998). Dynamic actuation of polyimide v-groove joints by electrical heating. *Sensors and Actuators A: Physical*, *67*(1-3), 199–204.

Emiliani, P., Stephanidis, C., Lindstroem, J., & Jannson, G. (1991). Access to pictorial information by blind people. *Issues in Telecommunication and Disability. Luxembourg: Commission of the European Communities*, 396–416.

Ernst, M., & Girouard, A. (2016a). Bending blindly: exploring bend gestures for the blind. In *Proceedings of the 2016 chi conference extended abstracts on human factors in computing systems* (pp. 2088–2096).

Ernst, M., & Girouard, A. (2016b). Exploring haptics for learning bend gestures for the blind. In *Proceedings of the 2016 chi conference extended abstracts on human factors in computing systems* (pp. 2097–2104).

Ernst, M., Swan, T., Cheung, V., & Girouard, A. (2017). Typhlex: Exploring deformable input for blind users controlling a mobile screen reader. *IEEE Pervasive Computing*, *16*(4), 28–35.

Etikan, I., Musa, S. A., & Alkassim, R. S. (2016). Comparison of convenience sampling and purposive sampling. *American journal of theoretical and applied statistics*, *5*(1), 1–4.

Fares, E., Cheung, V., & Girouard, A. (2017). Effects of bend gesture training on learnability and memorability in a mobile game. In *Proceedings of the 2017 acm international conference on interactive surfaces and spaces* (pp. 240–245).

Faustino, D. B., Nabil, S., & Girouard, A. (2020). Bend or pin: studying bend password authentication with people with vision impairment. In *Proceedings of the 20th international acm sigaccess conference on computers and accessibility (assets 2018)*

(pp. 435–437).

Fernando, S., & Ohene-Djan, J. (2021). A computer aided drawing system evaluation with early and late blind users. *Assistive Technology*, 1–10.

Fernando, S., & Ohene-Djan, J. (2022). A computer aided drawing system evaluation with early and late blind users. *Assistive Technology*, *34*(4), 392–401.

Freeman, W. T., & Roth, M. (1995). Orientation histograms for hand gesture recognition. In *International workshop on automatic face and gesture recognition* (Vol. 12, pp. 296–301).

Gallace, A., & Spence, C. (2020). A memory for touch: The cognitive psychology of tactile memory. In *Touch in museums* (pp. 163–186). Routledge.

Gallant, D. T., Seniuk, A. G., & Vertegaal, R. (2008). Towards more paper-like input: flexible input devices for foldable interaction styles. In *Proceedings of the 21st annual acm symposium on user interface software and technology* (pp. 283–286).

Garcez, A., Duarte, R., & Eisenberg, Z. (2011). Production and analysis of video recordings in qualitative research. *Educação e Pesquisa*, *37*, 249–261.

Giacomin, J. (2014). What is human centred design? *The Design Journal*, *17*(4), 606–623.

Girouard, A., Lo, J., Riyadh, M., Daliri, F., Eady, A. K., & Pasquero, J. (2015). One-handed bend interactions with deformable smartphones. In *Proceedings of the 33rd annual acm conference on human factors in computing systems* (pp. 1509–1518).

Goldreich, D., & Kanics, I. M. (2003). Tactile acuity is enhanced in blindness. *Journal of Neuroscience*, *23*(8), 3439–3445.

Goldreich, D., & Kanics, I. M. (2006). Performance of blind and sighted humans on a tactile grating detection task. *Perception & Psychophysics*, *68*(8), 1363–1371.

Gorlewicz, J. L., Burgner, J., Withrow, T. J., & Webster III, R. J. (2014). Initial experiences using vibratory touchscreens to display graphical math concepts to students with visual impairments. *Journal of Special Education Technology*, *29*(2), 17–25.

Gougoux, F., Lepore, F., Lassonde, M., Voss, P., Zatorre, R. J., & Belin, P. (2004). Pitch discrimination in the early blind. *Nature*, *430*(6997), 309–309.

Grandhi, S. A., Joue, G., & Mittelberg, I. (2011). Understanding naturalness and intuitiveness in gesture production: insights for touchless gestural interfaces. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 821–824).

Grech, A. M., Nakamura, J. P., & Hill, R. A. (2018). The importance of distinguishing allocentric and egocentric search strategies in rodent hippocampal-dependent spatial memory paradigms: getting more out of your data. *The Hippocampus-Plasticity and Functions*.

Grussenmeyer, W., & Folmer, E. (2016). Audiodraw: user preferences in non-visual diagram drawing for touchscreens. In *Proceedings of the 13th international web for all conference* (pp. 1–8).

Grussenmeyer, W., & Folmer, E. (2017). Accessible touchscreen technology for people with visual impairments: a survey. *ACM Transactions on Accessible Computing (TACCESS)*, *9*(2), 1–31.

Guidelines for assessment of disabilities under rpwd act. 2016 notified. (2018). Available at http://www.egazette.nic.in/WriteReadData/2018/181788.pdf (Last accessed on April 12, 2020).

Harrison, B. L., Fishkin, K. P., Gujar, A., Mochon, C., & Want, R. (1998). Squeeze me, hold me, tilt me! an exploration of manipulative user interfaces. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 17–24).

Harte, R., Glynn, L., Rodríguez-Molinero, A., Baker, P. M., Scharf, T., Quinlan, L. R., & ÓLaighin, G. (2017). A human-centered design methodology to enhance the usability, human factors, and user experience of connected health systems: a three-phase methodology. *JMIR human factors*, *4*(1), e5443.

Heller, M. A. (1992). The effect of orientation on tactual braille recognition: Optimal touching positions. *Perception & Psychophysics*, *51*(6), 549–556.

Heller, M. A., Calcaterra, J. A., Burson, L. L., & Tyler, L. A. (1996). Tactual picture identification by blind and sighted people: Effects of providing categorical information. *Perception & psychophysics*, *58*(2), 310–323.

Hoggan, E., Brewster, S. A., & Johnston, J. (2008). Investigating the effectiveness of tactile feedback for mobile touchscreens. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 1573–1582).

Holland, A. (2009). Audio description in the theatre and the visual arts: images into words. In *Audiovisual translation* (pp. 170–185). Springer.

Holman, D., Vertegaal, R., Altosaar, M., Troje, N., & Johns, D. (2005). Paper windows:

interaction techniques for digital paper. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 591–599).

Horsford, E. (2016). *Research with blind users on mobile devices.* https://accessibility.blog.gov.uk/2016/06/09/research-with-blind-users-on-mobile-devices/. (Last accessed on April 12, 2022)

Hospitál, L. (2017). *Why should students with visual impairment draw?* https://www.perkins.org/resource/why-should-students-visual-impairment-draw/. (Last accessed on April 12, 2022)

Hub, A., Diepstraten, J., & Ertl, T. (2003). Design and development of an indoor navigation and object identification system for the blind. *ACM Sigaccess Accessibility and Computing*(77-78), 147–152.

ISO. (2019). *Iso 9241-210: 2019 ergonomics of human-system interaction—part 210: Human-centred design for interactive systems.* Switzerland Geneva.

ISO, I. (2008). 7250-1: Basic human body measurements for technological design-part 1: Body measurement definitions and landmarks. *International Organization for Standardization, Geneva, Switzerland*.

Kamel, H. M., & Landay, J. A. (1999). The integrated communication 2 draw (ic2d) a drawing program for the visually impaired. In *Chi'99 extended abstracts on human factors in computing systems* (pp. 222–223).

Kamel, H. M., & Landay, J. A. (2000). A study of blind drawing practice: creating graphical information without the visual channel. In *Proceedings of the fourth international acm conference on assistive technologies* (pp. 34–41).

Kamel, H. M., & Landay, J. A. (2002a). Constructing moving pictures eyes-free: an animation tool for the blind. In *Chi'02 extended abstracts on human factors in computing systems* (pp. 772–773).

Kamel, H. M., & Landay, J. A. (2002b). Sketching images eyes-free: a grid-based dynamic drawing tool for the blind. In *Proceedings of the fifth international acm conference on assistive technologies* (pp. 33–40).

Kane, S. K., Bigham, J. P., & Wobbrock, J. O. (2008). Slide rule: making mobile touch screens accessible to blind people using multi-touch interaction techniques. In *Proceedings of the 10th international acm sigaccess conference on computers and accessibility* (pp.

73–80).

Kane, S. K., Jayant, C., Wobbrock, J. O., & Ladner, R. E. (2009). Freedom to roam: a study of mobile device adoption and accessibility for people with visual and motor disabilities. In *Proceedings of the 11th international acm sigaccess conference on computers and accessibility* (pp. 115–122).

Kane, S. K., Morris, M. R., & Wobbrock, J. O. (2013). Touchplates: low-cost tactile overlays for visually impaired touch screen users. In *Proceedings of the 15th international acm sigaccess conference on computers and accessibility* (pp. 1–8).

Karlson, A. K., & Bederson, B. B. (2007). Thumbspace: generalized one-handed input for touchscreen-based mobile devices. In *Ifip conference on human-computer interaction* (pp. 324–338).

Kelly, B., Sloan, D., Brown, S., Seale, J., Petrie, H., Lauke, P., & Ball, S. (2007). Accessibility 2.0: people, policies and processes. In *Proceedings of the 2007 international cross-disciplinary conference on web accessibility (w4a)* (pp. 138–147).

Kennedy, J. M. (1997). How the blind draw. *Scientific American*, *276*(1), 76–81.

Kennel, A. R. (1996). Audiograf: A diagram-reader for the blind. In *Proceedings of the second annual acm conference on assistive technologies* (pp. 51–56).

Khalilbeigi, M., Lissermann, R., Kleine, W., & Steimle, J. (2012). Foldme: interacting with double-sided foldable displays. In *Proceedings of the sixth international conference on tangible, embedded and embodied interaction* (pp. 33–40).

Kildal, J. (2012). Interacting with deformable user interfaces: effect of material stiffness and type of deformation gesture. In *International conference on haptic and audio interaction design* (pp. 71–80).

Kildal, J., & Boberg, M. (2013). Feel the action: dynamic tactile cues in the interaction with deformable uis. In *Chi'13 extended abstracts on human factors in computing systems* (pp. 1563–1568).

Kildal, J., Paasovaara, S., & Aaltonen, V. (2012). Kinetic device: designing interactions with a deformable mobile interface. In *Chi'12 extended abstracts on human factors in computing systems* (pp. 1871–1876).

Kildal, J., & Wilson, G. (2012). Feeling it: the roles of stiffness, deformation range and feedback in the control of deformable ui. In *Proceedings of the 14th acm international*

conference on multimodal interaction (pp. 393–400).

Kim, D. W., Kim, S. W., Lee, G., Yoon, J., Kim, S., Hong, J.-H., … Jeong, U. (2023). Fabrication of practical deformable displays: advances and challenges. *Light: Science & Applications*, *12*(1), 61.

Kim, S., Yu, J., & Lee, G. (2012). Interaction techniques for unreachable objects on the touchscreen. In *Proceedings of the 24th australian computer-human interaction conference* (pp. 295–298).

Klingenberg, O. G. (2007). Geometry: Educational implications for children with visual impairment. *Philosophy of Mathematics Education Journal*, *20*(15), 15.

Kurze, M. (1996). Tdraw: a computer-based tactile drawing tool for blind people. In *Proceedings of the second annual acm conference on assistive technologies* (pp. 131–138).

Lahey, B., Girouard, A., Burleson, W., & Vertegaal, R. (2011). Paperphone: understanding the use of bend gestures in mobile devices with flexible electronic paper displays. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 1303–1312).

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive psychology*, *19*(3), 342–368.

Lee, S. S., Kim, S., Jin, B., Choi, E., Kim, B., Jia, X., … Lee, K.-p. (2010). How users manipulate deformable displays as input devices. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 1647–1656).

Lee, Y. H., & Medioni, G. (2014). Wearable rgbd indoor navigation system for the blind. In *European conference on computer vision* (pp. 493–508).

Leporini, B., Buzzi, M. C., & Buzzi, M. (2012). Interacting with mobile devices via voiceover: usability and accessibility issues. In *Proceedings of the 24th australian computer-human interaction conference* (pp. 339–348).

Li, H., & Lim, S. (2022). Screen printing of surface-modified barium titanate/polyvinylidene fluoride nanocomposites for high-performance flexible piezoelectric nanogenerators. *Nanomaterials*, *12*(17), 2910.

Liu, H., Wang, J., Wang, X., & Qian, Y. (2015). isee: obstacle detection and feedback system for the blind. In *Adjunct proceedings of the 2015 acm international joint conference*

on pervasive and ubiquitous computing and proceedings of the 2015 acm international symposium on wearable computers (pp. 197–200).

Lo, J., & Girouard, A. (2014). Fabricating bendy: Design and development of deformable prototypes. *IEEE pervasive computing*, *13*(3), 40–46.

Lo, J., & Girouard, A. (2017). Bendy: Exploring mobile gaming with flexible devices. In *Proceedings of the eleventh international conference on tangible, embedded, and embodied interaction* (pp. 163–172).

Macdonell, A. A. (2004). *A practical sanskrit dictionary with transliteration, accentuation, and etymological analysis throughout*. Motilal Banarsidass Publ.

Malhotra, S., Vashist, P., Kalaivani, M., Gupta, N., Senjam, S. S., Rath, R., & Gupta, S. K. (2018). Prevalence and causes of visual impairment amongst older adults in a rural area of north india: a cross-sectional study. *Bmj Open*, *8*(3), e018894.

Manduchi, R., & Coughlan, J. (2012). (computer) vision without sight. *Communications of the ACM*, *55*(1), 96–104.

Maqsood, S., Chiasson, S., & Girouard, A. (2016). Bend passwords: using gestures to authenticate on flexible devices. *Personal and Ubiquitous Computing*, *20*(4), 573–600.

McGookin, D., Robertson, E., & Brewster, S. (2010). Clutching at straws: using tangible interaction to provide non-visual access to graphs. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 1715–1724).

McGookin, D. K., & Brewster, S. A. (2006a). Multivis: improving access to visualisations for visually impaired people. In *Chi'06 extended abstracts on human factors in computing systems* (pp. 267–270).

McGookin, D. K., & Brewster, S. A. (2006b). Soundbar: exploiting multiple views in multimodal graph browsing. In *Proceedings of the 4th nordic conference on human-computer interaction: changing roles* (pp. 145–154).

McLaughlin, M. (2019). *Make your life easier with android's accessibility features*. Available at https://www.lifewire.com/make-your-life-easier-with-androids-accessibility-features-4064537 (Last accessed on April 12, 2021).

Memeo, M., Jacono, M., Sandini, G., & Brayda, L. (2021). Enabling visually impaired people to learn three-dimensional tactile graphics with a 3dof haptic mouse. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–21.

Metatla, O., Bryan-Kinns, N., & Stockman, T. (2008). Comparing interaction strategies for constructing diagrams in an audio-only interface. *People and Computers XXII Culture, Creativity, Interaction 22*, 65–69.

Miller, D. (2006). *Accessible diagram interfaces*. Citeseer.

Monga, P. K., Parwal, B. P., Rohatgi, J., & Dhaliwal, U. (2009). Are current guidelines for categorization of visual impairment in india appropriate? *Indian journal of ophthalmology*, *57*(6), 423.

Monier-Williams, M. (1964). *Sanskrit-english dictionary*. Рипол Классик.

Morris, M. R., Danielescu, A., Drucker, S., Fisher, D., Lee, B., Schraefel, M., & Wobbrock, J. O. (2014). Reducing legacy bias in gesture elicitation studies. *interactions*, *21*(3), 40–45.

Muller, M. J., & Kuhn, S. (1993). Participatory design. *Communications of the ACM*, *36*(6), 24–28.

Nathan, A., Ahnood, A., Cole, M. T., Lee, S., Suzuki, Y., Hiralal, P., … Milne, W. I. (2012). Flexible electronics: the next ubiquitous platform. *Proceedings of the IEEE*, *100*(Special Centennial Issue), 1486–1517.

National Handicapped Finance and Development. (2021). *Persons with disabilities (divyangjan) in india - a statistical profile : 2021*. http://www.nhfdc.nic.in/upload/nhfdc/Persons_Disabilities_31mar21.pdf. (Last accessed on April 11, 2022)

National Programme for Control of Blindness & Visual Impairment. (2019). *National blindness and visual impairment survey india 2015-19- a summary report*. https://npcbvi.gov.in/writeReadData/mainlinkFile/File341.pdf. (Last accessed on April 15, 2021)

Nicolau, H., Montague, K., Guerreiro, T., Rodrigues, A., & Hanson, V. L. (2015). Typing performance of blind users: An analysis of touch behaviors, learning effect, and in-situ usage. In *Proceedings of the 17th international acm sigaccess conference on computers & accessibility* (pp. 273–280).

Nielsen, J. (2020). *Ten usability heuristics*. https://www.nngroup.com/articles/ten-usability-heuristics/.

Nishino, H., Goto, R., Kagawa, T., Yoshida, K., Utsumiya, K., Hirooka, J., … Aoki, E. (2011).

A touch screen interface design with tactile feedback. In *2011 international conference on complex, intelligent, and software intensive systems* (pp. 53–60).

Norman, D. A. (1986). New views of information processing: Implications for intelligent decision support systems. In *Intelligent decision support in process environments* (pp. 123–136). Springer.

Norman, D. A., & Draper, S. W. (1986). *User centered system design: New perspectives on human-computer interaction*. CUMINCAD.

Oh, U., Kane, S. K., & Findlater, L. (2013). Follow that sound: using sonification and corrective verbal feedback to teach touchscreen gestures. In *Proceedings of the 15th international acm sigaccess conference on computers and accessibility* (pp. 1–8).

Oliveira, J., Guerreiro, T., Nicolau, H., Jorge, J., & Gonçalves, D. (2011). Brailletype: unleashing braille over touch screen mobile phones. In *Ifip conference on human-computer interaction* (pp. 100–107).

Oswal, S. K. (2014). Participatory design: Barriers and possibilities. *Communication Design Quarterly Review*, *2*(3), 14–19.

Pal, J., & Lakshmanan, M. (2012). Assistive technology and the employment of people with vision impairments in india. In *Proceedings of the fifth international conference on information and communication technologies and development* (pp. 307–317).

Parthasarathy, B., Dey, S., & Gupta, P. (2021). Overcoming wicked problems and institutional voids for social innovation: University-ngo partnerships in the global south. *Technological Forecasting and Social Change*, *173*, 121104.

Patil, K., Jawadwala, Q., & Shu, F. C. (2018). Design and construction of electronic aid for visually impaired people. *IEEE Transactions on Human-Machine Systems*, *48*(2), 172–182.

Perego, E. (2018). Audio description: Evolving recommendations for usable, effective and enjoyable practices. In *The routledge handbook of audiovisual translation* (pp. 114–129). Routledge.

Perneger, T. V. (1998). What's wrong with bonferroni adjustments. *Bmj*, *316*(7139), 1236–1238.

Pheasant, S., & Haslegrave, C. M. (2018). *Bodyspace: Anthropometry, ergonomics and the design of work*. CRC press.

Phillips, M., & Proulx, M. J. (2018). Social interaction without vision: an assessment of assistive technology for the visually impaired. *Technology & Innovation*, *20*(1-2), 85–93.

Phutane, M., Wright, J., Castro, B. V., Shi, L., Stern, S. R., Lawson, H. M., & Azenkot, S. (2022). Tactile materials in practice: Understanding the experiences of teachers of the visually impaired. *ACM Transactions on Accessible Computing*.

Post, L., Zompa, I., & Chapman, C. (1994). Perception of vibrotactile stimuli during motor activity in human subjects. *Experimental brain research*, *100*(1), 107–120.

Potter, R. L., Weldon, L. J., & Shneiderman, B. (1988). Improving the accuracy of touch screens: an experimental evaluation of three strategies. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 27–32).

Puig-Diví, A., Escalona-Marfil, C., Padullés-Riu, J. M., Busquets, A., Padulles-Chando, X., & Marcos-Ruiz, D. (2019). Validity and reliability of the kinovea program in obtaining angles and distances using coordinates in 4 perspectives. *PloS one*, *14*(6), e0216448.

Ramamoorthy, A., Vaswani, N., Chaudhury, S., & Banerjee, S. (2003). Recognition of dynamic hand gestures. *Pattern Recognition*, *36*(9), 2069–2081.

Rassmus-Gröhn, K., Magnusson, C., & Eftring, H. E. (2007). Iterative design of an audio-haptic drawing application. In *Chi'07 extended abstracts on human factors in computing systems* (pp. 2627–2632).

Rector, K., Bartlett, R., & Mullan, S. (2018). Exploring aural and haptic feedback for visually impaired people on a track: A wizard of oz study. In *Proceedings of the 20th international acm sigaccess conference on computers and accessibility* (pp. 295–306).

Rodrigues, A., Montague, K., Nicolau, H., & Guerreiro, T. (2015). Getting smartphones to talkback: Understanding the smartphone adoption process of blind users. In *Proceedings of the 17th international acm sigaccess conference on computers & accessibility* (pp. 23–32).

Romero, M., Frey, B., Southern, C., & Abowd, G. D. (2011). Brailletouch: designing a mobile eyes-free soft keyboard. In *Proceedings of the 13th international conference on human computer interaction with mobile devices and services* (pp. 707–709).

Roudaut, A., Huot, S., & Lecolinet, E. (2008). Taptap and magstick: improving one-handed target acquisition on small touch-screens. In *Proceedings of the working conference on*

advanced visual interfaces (pp. 146–153).

Rouzier, S., Hennion, B., Segovia, T. P., & Chêne, D. (2004). Touching geometry for blind pupils. In *International conference on computers for handicapped persons* (pp. 697–704).

Sahasrabudhe, S., & Palvia, P. (2013). Academic challenges of blind students and their mitigation strategies. In *Proceedings of the nineteenth americas conference on information systems, chicago, illinois* (pp. 15–17).

Sakhardande, P., Joshi, A., Jadhav, C., & Joshi, M. (2019). Comparing user performance on parallel-tone, parallel-speech, serial-tone and serial-speech auditory graphs. In *Ifip conference on human-computer interaction* (pp. 247–266).

Salway, A. (2007). A corpus-based analysis of audio description. In *Media for all* (pp. 151–174). Brill.

Schuler, D., & Namioka, A. (1993). *Participatory design: Principles and practices*. CRC Press.

Schwesig, C., Poupyrev, I., & Mori, E. (2003). Gummi: user interface for deformable computers. In *Chi'03 extended abstracts on human factors in computing systems* (pp. 954–955).

Schwesig, C., Poupyrev, I., & Mori, E. (2004). Gummi: a bendable computer. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 263–270).

Senjam, S. S., Foster, A., & Bascaran, C. (2021). Barriers to using assistive technology among students with visual disability in schools for the blind in delhi, india. *Disability and Rehabilitation: Assistive Technology*, *16*(7), 802–806.

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, *52*(3/4), 591–611.

Sherard, W. H. (1981). Why is geometry a basic skill? *The Mathematics Teacher*, *74*(1), 19–60.

Shneiderman, B., Plaisant, C., Cohen, M. S., Jacobs, S., Elmqvist, N., & Diakopoulos, N. (2016). *Designing the user interface: strategies for effective human-computer interaction*. Pearson.

Shoval, S., Borenstein, J., & Koren, Y. (1998). The navbelt-a computerized travel aid for the blind based on mobile robotics technology. *IEEE Transactions on Biomedical*

Engineering, *45*(11), 1376–1386.

Simões-Franklin, C., Whitaker, T. A., & Newell, F. N. (2011). Active and passive touch differentially activate somatosensory cortex in texture perception. *Human brain mapping*, *32*(7), 1067–1080.

Smith, D. W. (2006). Developing mathematical concepts through orientation and mobility. *RE VIEW*, *37*(4), 161.

Sorathia, K., Singh, A., & Chhabra, M. (2017). Bendswipe: One handed target zooming for flexible handheld display. In *Ifip conference on human-computer interaction* (pp. 431–435).

Steimle, J., Jordt, A., & Maes, P. (2013). Flexpad: highly flexible bending interactions for projected handheld displays. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 237–246).

Strohmeier, P., Burstyn, J., Carrascal, J. P., Levesque, V., & Vertegaal, R. (2016). Reflex: A flexible smartphone with active haptic feedback for bend input. In *Proceedings of the tei'16: Tenth international conference on tangible, embedded, and embodied interaction* (pp. 185–192).

Struiksma, M. E., Noordzij, M. L., & Postma, A. (2009). What is the link between language and spatial images? behavioral and neural findings in blind and sighted individuals. *Acta Psychologica*, *132*(2), 145–156.

Systems, T. (2017). *Bending. main concepts and capabilities.* Available at https://www.tflex.com/help/eng/T-FLEX%20CAD/15/index.html?smb.htm (Accessed on January 15, 2021).

Szubielska, M. (2014). Strategies for constructing spatial representations used by blind and sighted subjects. *Studia Psychologica*, *56*(4), 273.

Tajika, T., Yonezawa, T., & Mitsunaga, N. (2008). Intuitive page-turning interface of e-books on flexible e-paper based on user studies. In *Proceedings of the 16th acm international conference on multimedia* (pp. 793–796).

Tao, Y., Han, F., Shi, C., Yang, R., Chen, Y., & Ren, Y. (2022). Liquid metal-based flexible and wearable sensor for functional human–machine interface. *Micromachines*, *13*(9), 1429.

Taraporevala, S. (2016). Stem education for blind and low vision students the socio-technical

challenge: The indian perspective. In *The 3rd international workshop on digitization and e-inclusion in mathematics and science 2016 (deims2016)*.

Thinus-Blanc, C., & Gaunet, F. (1997). Representation of space in blind persons: vision as a spatial sense? *Psychological bulletin*, *121*(1), 20.

Toennies, J. L., Burgner, J., Withrow, T. J., & Webster, R. J. (2011). Toward haptic/aural touchscreen display of graphical mathematics for the education of blind students. In *2011 ieee world haptics conference* (pp. 373–378).

Trewin, S., Swart, C., & Pettick, D. (2013). Physical accessibility of touchscreen smartphones. In *Proceedings of the 15th international acm sigaccess conference on computers and accessibility* (pp. 1–8).

Tukey, J. W. (1977). *Exploratory data analysis* (Vol. 2). Reading, MA.

van Oosterhout, A., & Hoggan, E. (2021). Deformation techniques for shape changing interfaces. In *Extended abstracts of the 2021 chi conference on human factors in computing systems* (pp. 1–7).

Vashistha, A., Brady, E., Thies, W., & Cutrell, E. (2014). Educational content creation and sharing by low-income visually impaired people in india. In *Proceedings of the fifth acm symposium on computing for development* (pp. 63–72).

Velázquez, R. (2010). Wearable assistive devices for the blind. In *Wearable and autonomous biomedical devices and systems for smart environment* (pp. 331–349). Springer.

Vinter, A., Bonin, P., & Morgan, P. (2018). The severity of the visual impairment and practice matter for drawing ability in children. *Research in developmental disabilities*, *78*, 15–26.

Vogel, D., Cudmore, M., Casiez, G., Balakrishnan, R., & Keliher, L. (2009). Hand occlusion with tablet-sized direct pen input. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 557–566).

Waller, A. (2021). Participatory design and research: Challenges for augmentative and alternative communication technologies. In *The 23rd international acm sigaccess conference on computers and accessibility* (pp. 1–1).

Warren, K., Lo, J., Vadgama, V., & Girouard, A. (2013). Bending the rules: bend gesture classification for flexible displays. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 607–610).

Watanabe, J. I., Mochizuki, A., & Horry, Y. (2008). Bookisheet: bendable device for browsing content using the metaphor of leafing through the pages. In *Proceedings of the 10th international conference on ubiquitous computing* (pp. 360–369).

Watanabe, T., & Kobayashi, M. (2002). A prototype of the freely rewritable tactile drawing system for persons who are blind. *Journal of Visual Impairment & Blindness*, *96*(6), 460–464.

Wersényi, G. (2009). Auditory representations of a graphical user interface for a better human-computer interaction. In *Auditory display* (pp. 80–102). Springer.

Whitaker, R. (2020). Android accessibility features. In *Developing inclusive mobile apps* (pp. 93–137). Springer.

White, G. R., Fitzpatrick, G., & McAllister, G. (2008). Toward accessible 3d virtual environments for the blind and visually impaired. In *Proceedings of the 3rd international conference on digital interactive media in entertainment and arts* (pp. 134–141).

Wightman, D., Ginn, T., & Vertegaal, R. (2011). Bendflip: examining input techniques for electronic book readers with flexible form factors. In *Ifip conference on human-computer interaction* (pp. 117–133).

Wobbrock, J. O., Aung, H. H., Rothrock, B., & Myers, B. A. (2005). Maximizing the guessability of symbolic input. In *Chi'05 extended abstracts on human factors in computing systems* (pp. 1869–1872).

Wobbrock, J. O., Morris, M. R., & Wilson, A. D. (2009). User-defined gestures for surface computing. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 1083–1092).

Wong, E. (2020). *Shneiderman's eight golden rules will help you design better interfaces.* https://www.interaction-design.org/literature/article/shneiderman-s-eight-golden-rules-will-help-you-design-better-interfaces. (Last accessed on April 12, 2022)

Wong, W. S., Chabinyc, M. L., Ng, T.-N., & Salleo, A. (2009). Materials and novel patterning methods for flexible electronics. In *flexible electronics* (pp. 143–181). Springer.

World Access for the Blind. (2015). *Blindness: Challenge and achievement.* https://waftb.net/blindness-challenge-and-achievement. (Last accessed on April 12, 2022)

Wu, Y., Ma, Y., Zheng, H., & Ramakrishna, S. (2021). Piezoelectric materials for flexible and wearable electronics: A review. *Materials & Design*, 110164.

Xu, S., Yang, C., Ge, W., Yu, C., & Shi, Y. (2020). Virtual paving: Rendering a smooth path for people with visual impairment through vibrotactile and audio feedback. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, *4*(3), 1–25.

Xu, Z., Li, R., Li, H., Gao, G., & Chen, T. (2022). Flexible and adhesive liquid-free ionic conductive elastomers toward human–machine interaction. *Soft Matter*, *18*(37), 7103–7111.

Yu, W., Kangas, K., & Brewster, S. (2003). Web-based haptic applications for blind people to create virtual graphs. In *11th symposium on haptic interfaces for virtual environment and teleoperator systems, 2003. haptics 2003. proceedings.* (pp. 318–325).

Zebehazy, K. T., & Wilton, A. P. (2014). Straight from the source: Perceptions of students with visual impairments about graphic use. *Journal of Visual Impairment & Blindness*, *108*(4), 275–286.

Zhang, C., Jiang, N., & Tian, F. (2016). Accessing mobile apps with user defined gesture shortcuts: An exploratory study. In *Proceedings of the 2016 acm international conference on interactive surfaces and spaces* (pp. 385–390).

Zhang, H., & Li, Y. (2014). Gestkeyboard: enabling gesture-based interaction on ordinary physical keyboard. In *Proceedings of the sigchi conference on human factors in computing systems* (pp. 1675–1684).

Zhang, Z., & Wobbrock, J. O. (2022). A11yboard: Using multimodal input and output to make digital artboards accessible to blind users. In *Adjunct proceedings of the 35th annual acm symposium on user interface software and technology* (pp. 1–4).

Zhao, K., Bardot, S., Serrano, M., Simonnet, M., Oriola, B., & Jouffrais, C. (2021). Tactile fixations: A behavioral marker on how people with visual impairments explore raised-line graphics. In *Proceedings of the 2021 chi conference on human factors in computing systems* (pp. 1–12).

Zhou, Z., Zhang, H., Liu, J., & Huang, W. (2021). Flexible electronics from intrinsically soft materials. *Giant*, *6*, 100051.

List of Publications

1. Pranjal Protim Borah and Keyur Babulal Sorathia (2019). Direct observation of tactile geometric drawing by visually impaired and blind students. In Proceedings of the Tenth Indian Conference on Human-computer Interaction, Association for Computing Machinery (ACM).
   DOI: https://doi.org/10.1145/3364183.3364185

2. Pranjal Protim Borah and Keyur Babulal Sorathia (2021). Learning and creating mathematical diagrams: Findings of a retrospective study conducted with users with blindness or low vision. In Proceedings of the Twelfth Indian Conference on Human-computer Interaction, Association for Computing Machinery (ACM).
   DOI: https://doi.org/10.1145/3506469.3506486

3. Pranjal Protim Borah, Keyur Babulal Sorathia and Sayan Sarcar (2021). User-defined bend gesture completion strategies for discrete and continuous inputs. Human-Computer Interaction – INTERACT, Springer.
   DOI: https://doi.org/10.1007/978-3-030-85613-7_14

4. Pranjal Protim Borah and Keyur Babulal Sorathia (2022). Fabrication of Nāmya: A bend and touch-sensitive flexible smartphone-sized prototype. Human Behavior and Emerging Technologies, Hindawi.
   DOI: https://doi.org/10.1155/2022/1205420

5. Pranjal Protim Borah and Keyur Babulal Sorathia (2023). Investigating User Performance and Preference for Two Magnitude Levels of Size and Angle of Bend on a Smartphone-sized Flexible Device. Behaviour and Information Technology, Taylor & Francis.
   DOI: https://doi.org/10.1080/0144929X.2023.2245062