An Exploratory Study of Marking Menu Selection by Visually Impaired Participants

Nem Khan Dim[1], Kibum Kim[1,2], Xiangshi Ren[1]
[1]The Center for Human-Engaged Computing
Kochi University of Technology, Kochi, Japan
nemkdim@gmail.com,hamyndanda@gmail.com, xsren@acm.org
[2]Keimyung University, Daegu, Korea
kibumkim@kmu.ac.kr

***Abstract*—Although there have been recent advances in smartphone accessibility for blind people, they rely on screen readers and voice commands which are not ideal for users with visual impairment in mobile situations. By contrast, recent research has shown that marking menus would be beneficial to users' eyes-free interactions. However, the literature lacks accessibility implications and adaptation to the needs of blind people. This paper investigates blind people's capabilities to perform marking menu selections using the 3D motion of a smartphone in order to invoke smartphone functions. We present the bounds and range of marking gestures that a blind person can perform at each level, and the number of levels that a blind person can successfully cope with. Based on the experiment results, we also presented design guidelines.**

Keywords—marking gestures; accessibility; 3D motion

I. Introduction

Even though some accessibility issues remain with smart-phones, blind users' reliance on smartphones has been increasing [30]. Although smartphones support screen readers and voice commands for visually impaired users, these features can be inefficient in noisy environments and inappropriate in quiet public environments. Current accessibility features in smartphones such as VoiceOver and TalkBack [17] enable blind users to browse menu items on touch screens using speech feedback. However, these systems require users to perform long sequences of touch gestures to browse the menus. This can result in increased user fatigue and dissatisfaction. There is a pressing need for efficient interactions as a supplement or an alternative to the accessibility features that are currently available.

In mobile situations, blind users mostly have one hand occupied with a cane or a guide dog [30]. For the purpose of use "on the go," 3D motion gestures are desirable because they provide natural and fast access with more freedom, and they enable users to operate the system using only one hand [25, 28]. Fortunately, adequate motion sensors are now available on most common mobile devices to make this possible.

Literature has shown that marking menus are readily adapted to mobile devices because they offer fast and eyes-free interaction [7, 8]. This indicates that marking gestures can offer significant benefits to blind users for eyes-free mobile interactions. First, marking gestures can be embedded into muscle memory as the user rehearses the physical movement every time a menu selection is made [20]. A previous study also demonstrated that spatial and kinesthetic memory is used when vision is limited or unavailable [9]. Second, users easily remember, recall and perform marking gestures for the most frequently used menu items, thus tasks can be completed faster than when browsing linear menus. Third, straight marking gestures are easier for users to perform and easier for systems to recognize. Thus, we propose that marking menus working together with motion gestures can provide more natural and efficient eyes-free interaction.

In spite of the potential, the capability of blind people to perform motion spatial gestures for eyes-free interaction has not been investigated. A sound understanding of such capabilities will help in the design of more efficient and accessible interfaces for blind people. We were thus motivated to investigate accessibility implications in designing motion-based marking gestures for blind people.

This study seeks to investigate a blind person's ability to perform directional motion gestures. User experiment was conducted to answer the following research questions: 1) How many menu items can there be at each level? In other words, we wanted to determine how many directions a blind person can distinguish to successfully perform marking gestures. 2) How deep or how many hierarchy levels can a blind person can go to perform marking gestures? 3) Is breadth better than depth or vice versa?

To answer the aforementioned research questions, we performed user experiments. In our experiment, we investigated the number of directions and levels in which a blind person can perform marking gestures, and breadth/ depth trade-offs when designing motion-based marking gestures for blind people.

Results from our experiment indicated that blind people are able to perform directional gestures in up to 8 directions. The results also suggested that hierarchic levels for marking gestures are efficient up to 4 levels for 4-item menus, up to 2 levels for 6-item menus and up to 3 levels for 8-item menus. Based on the qualitative data from our experiment, we provided design implications and guidelines for marking gestures and motion-based marking menus on smartphones.

II. Related work

Related work includes marking menus for mobile devices, mobile device accessibility for blind people and mobile spatial interactions.

A. *Marking Menus on Mobile Devices*

Kurtenbach et al. [21] proposed and evaluated marking menus that allow users to perform menu selection by either selecting an item from a pop-up menu or drawing marks in the direction of the desired menu item. Marking menus have been adapted to various applications and devices including desktop computing [27], handheld devices [8] and remote interactions [2].

Recently, marking menus have been adapted to mobile interactions because they offer fast and eyes-free interactions. Jain and Balakrishnan developed a marking gesture based text entry system which requires less visual attention from users [16]. The pieTouch is a marking gesture based vehicle information system designed to reduce visual demand [7]. Francone et al. presented a touch based marking menus for navigating data hierarchies on mobile phones [8]. Although not focused on accessibility, Oakley and Park demonstrated a marking menu based eyes-free menu system with 3D rotational strokes [26]. This system deviates from the traditional marking menu system in that it is one dimensional and the system involves dividing a 90-degree portion of rotational space into three targets of 30 each. Bauer et al. presented a marking menu system for eyes-free interactions with large displays using smartphones and tablets [2]. In their study, a marking menu was placed on the touch screen of smartphones and tablets so that the users could remotely interact with large displays. Despite the notion that marking gestures can be a promising eyes-free input modality, accessibility related questions about a blind people's capability to perform marking gestures have not been fully investigated.

Our goal is to investigate the extent of efficiency and comfort with which a blind person can perform using marking gestures and to identify accessibility implications for designing marking gestures as for eyes-free inputs for blind people.

B. *Mobile Device Accessibility for Blind People*

Past studies have attempted to provide blind people with more accessibility to mobile devices, including smartphones and touch screen-based systems. Kane et al. presented a specialized touch interface for menu selections, "Slide Rule" that was optimized for non-visual interaction [18]. Slide Rule is a set of audio-based multi touch interaction techniques that enable blind users to access smartphone functions including making phone calls, mailing and performing music functions. Zhao et al. developed EarPod using touch input and sound feedback for eyes-free menu selection [33]. Audio-based text entry systems were also developed by Sancheznchez and Aguayo [29] and Yfantidis and Evreinov [32]. These systems used multi-tap and directional gestures and audio feedback, to enable users to enter text on touch screens.

In mobile situations, blind users mostly have one hand occupied with a cane or a guide dog [30] while touch based interfaces may require users to use both hands, one hand for holding the phone and one hand for performing gestures. Although touch based interfaces enable one hand operation using the thumb, user's performance in interactions greatly rely on the surface size, hand size and hand posture, etc. [3]. For the purpose of use "on the go", 3D motion gestures are desirable because they provide fast access and enable users to operate the system using only one hand [25, 28]. Also, a previous study has reported that motion gestures offered desirable interfaces and they were receptive to blind users [6]. Thus, we were motivated to investigate the efficacy of motion gestures working together with marking menus on mobile devices for blind people.

C. *Mobile Spatial Interactions*

Spatial interfaces were classified as head, body or world-stabilized [4]. Nowadays, mobile devices are augmented with sensing techniques to support more spontaneous and faster ways of interacting. Recently, there has been a growing interest in research regarding input techniques in mobile devices that allow spatial input beyond a touch screen. For example, SideSight [5], Abracadabra [11], Minput [12], Skinput [13] and HoverFlow [19] provide spatial inputs in mobile devices. Peephole displays [31] offer spatial input that maps physical movements of a device to movements in a virtual world.

VirtualShelves [22, 23] extends these techniques in a way by treating the space around the user as a discrete set of regions (shelves), so that the user could access contents on the virtual shelves. Gustafson et al. [10] presented Imaginary Interfaces which are spatial interactions that occur only in the users imagination.

Our study investigates how well blind users can define an invisible interaction space, and how well they can perform spatial gestures for eyes-free interactions.

III. PRELIMINARY INTERVIEWS

Before the experimental studies, we conducted a preliminary interview with 10 blind people (ages range from 27 to 78 years). 5 of them were totally blind, 2 of them could distinguish light and dark, and 3 of them could see objects but could not distinguish. The interview for each participant took around one hour. Each participant was paid $10 for their participation.

The purpose of the interview was to investigate (i) current problems with mobile phones that they were already using, (ii) the potential of marking gestures and spatial interactions as eyes-free interfaces for blind people, (iii) spatial awareness of blind people in their daily lives.

A. *Current Problems with Mobile Phones*

We investigated the current usage of mobile phones by our participants. Seven of them used feature phones and the other 3 used smartphones. When asked about their current mobile phone usage, the feature phone users commented mostly on the limited features in their mobile phones and the need of faster operation. All of them mentioned that they would like to have more access to more utilities such as GPS, calendar, weather, etc. The smartphone users mostly commented on the fatigue they experience using their smartphones. Current accessibility features in smartphones support flick gestures and speech output to browse menus on the screen. One of our participants stated, "Many times (when using the smartphone), I want to skip the cursor. Sometimes the guiding voice is frustrating and awkward in public places." This encouraged us to test the efficacy of the marking menu system as a solution to problems with current accessibility features.

B. *Potential of Makring Gestures and Spatial Interactions*

Through the interview study, we learned that many interactions in the daily lives of blind people are facilitated by spatial awareness and kinesthetic memory. During the interview, all participants consistently mentioned that performing their daily tasks was mostly facilitated by touching, relocating objects that they use each day and memorizing habits that they learned through repetition. When asked about daily tasks that they could successfully perform by repeating and habit, one of the participants stated, "I can put an appropriate amount of water into a jug to make coffee even though I cannot see it." The same participant mentioned, "It is not that difficult to do daily tasks. But I am in trouble if someone has moved things that I usually use."

The important point to note with marking menus is that the physical movements performed when selecting a menu item are rehearsed and learned into the user's muscle memory. Thus, we were convinced that marking gestures could be used as eyes-free interactions for blind people.

C. *Spatial Awareness*

When asked about their awareness of directions, all participants expressed difficulty in figuring out directions in terms of cardinal directions (i.e. North, West, etc.). Most of the participants were less familiar with directions either in terms of a compass (N, S, W, E) or in terms of the twelve divisions on the dial of a clock or watch (e.g. "at 2 o'clock"). One of the participants mentioned, "I can roughly say directions of hours on a clock because I used a tactile watch before. For example, 8 o'clock would be at the lower-left of my body." Another participant stated, "I have never used a compass though a compass with sound or texture would be usable." The same participant mentioned, "Nowadays, it is very easy to use digital clocks with sound, so, I am not familiar with the directions on a clock." Instead, they all agreed that directions relative to their body (i.e. left, right, etc.) were easy to understand and that they frequently use those directions to arrange their daily items. One participant mentioned, "I put my daily items around my chair where I can easily access them, for example, my mobile phone at my right side, my radio or charger at my left side." All of the participants consistently mentioned that they preferred saying directions using left/ right because they are constant (related to the body). The answers regarding spatial awareness suggested that blind persons' familiarity with compass or clock layouts depends on individuals training in visual thinking (e.g., whether they were exposed to and taught to read braille clocks or a raised compass). Thus, we were informed that directions in our experimental tasks should be limited to those that can be labeled relative to the human body (i.e. left, right, upper-left, etc.), and it might not be possible to include twelve directions labeled according to the hours on a clock.

Being informed by the interview study about the potential of marking gestures and spatial interactions for blind people, we conducted user studies to investigate the extent of efficiency and comfort with which a blind person can perform marking gestures. We then investigated the efficacy of marking menus as a solution to the current problems experienced by blind participants.

IV. EXPERIMENT

Experiment was conducted to answer the questions, 1) how many menu items can there be at each level? 2) how deep or how many hierarchy levels a blind person can go to perform marking gestures? 3) is breadth better than depth or vice versa?

A. *Design*

Trials to establish the number of items (breadth) and number of levels (depth) were within-subject. The participants performed target selections in 12 target configurations, 4 x breadth (angular width 90), 6 x breadth (angular width 60) and 8 x breadth (angular width 45) crossed with depths from 1 to 4. The rationales for selecting the number of items and levels were based on findings from our interview study and the experiment design from a previous marking menu study [21]. In [21], the experimental design used 13 menu configurations (breadths of 4, 8 and 12 crossed with depths from 1 to 4, plus a mixed configuration of 12:8:12 labeling the menu positions as cardinal directions and hours on a clock). Our interview study informed us that most of blind people may not be aware of directions derived from clocks. Thus, we removed menu configurations with of 12 items from our study. Instead, we added 6 item menus that can be labeled relative to the human body (i.e. left, upper-right, right, etc.). We added 6 item menus because we hypothesized that this menu configuration can be a good option in case menu selections in 8-item menus are were too error prone for blind people.

In each target configuration, four different targets were presented. Each target was presented 3 times. We picked four targets for each target configuration such that both easy and difficult targets were included. Easy targets were those that existed along vertical and horizontal axes (i.e. left, right, up, down). Difficult targets were those that existed in off-axis positions (i.e. upper-left, upper-right, etc.). We paid attention to ensure that target selections in our study included easy, moderately difficult and difficult targets. Each participant performed:

12 target configurations x
4 targets x
3 repetitions
= 144 target selections in total

The order of the targets was counterbalanced using a Latin Square. The occurrence of target configurations was randomized among the participants.

B. *Participants and Apparatus*

Thirteen blind participants (2 females and 11 male), with ages ranging from 26 to 78 years, participated in the experiment. One of the participants could see the light and three of them could see objects, but none were able to distinguish between objects. The rest were totally blind. All the participants were right-handed. Each was paid $10 for their participation.

We used a Leap Motion sensor (accuracy rate 200 fps) to capture the participants hand gestures. The gesture recognizer was written in .Net C#. All the experiment trials were video recorded. The motion capturing system used in the study is shown in Figure 1.

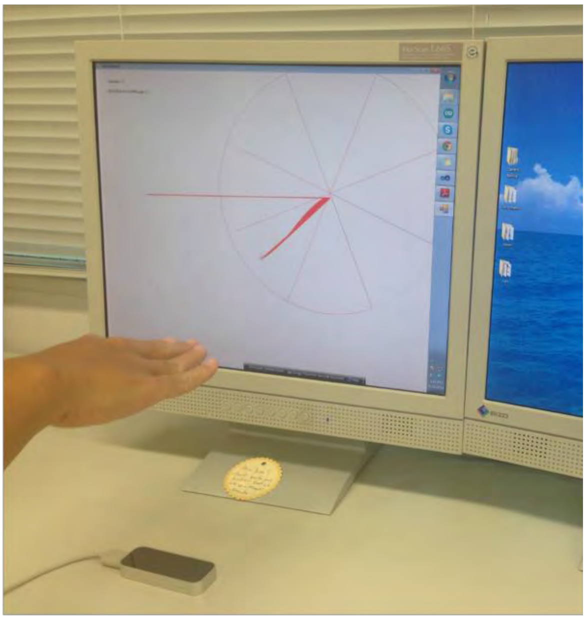

Fig. 1. Motion capturing system and target selection by participant.

C. Procedure

Before starting experimental trials, the target configurations were explained to the participants. To become familiar with the system, the participants were allowed two practice trials on 4x1 menus. We used a GUI interface to see the participants hand movements and target selections. Each experimental trial occurred as follows. The participant showed a hand in front of the screen and a pie menu appeared with the center point at the position of the participants' fingertip. Then, the experimenter read out the target that was to be selected. Once a target had been read out, the participant responded by moving the hand to the target. The participants confirmed their gestures by having their hands dwell within the target area for 0.7 seconds. The direction of hand movements and selected targets were recorded both by the system and the experimenter. Errors and response times were recorded during the study. The experiment ended with the participant answering a set of questionnaires and making questions or comments if they had any. The experiment for each participant took around one hour.

D. Result

The data of interest were error rates and response times. Error rates were measured by the percentage of incorrect selections out of 12 trials in a particular target configuration. Response time was defined as the time elapsed between the display of the target until the completion of the gesture by the participant. Before analyzing the data, we removed errors caused by "mental slip" [21]. For example, sometimes when instructed to select the target on the left, participant would accidently move the hand to the right. We did not include these types of errors in the data sets because they were not caused by selection inaccuracies.

Breadth significantly affected the error rates ($F(2,24)=30.83$, $p<0.05$). Error rates also increased as the number of levels increased ($F(3,36)=105.868$, $p<0.05$). Also, both breadth and depth interacted to affect error rates ($F(6,72)=21.834$, $p<0.05$). Figure 2 shows these relationships. All participants were able to select a target from a 4-item menu without any errors up to level 2. Although we hypothesized that 6-item menus may be less error-prone than 8-item menus because of the larger target sizes, error rates in six-item menus dramatically increased in level 3. This is because the participants made more errors when the targets existed "off-axis" and, in 6-item menus, most of the targets existed "off-axis" (60, 120, 240 and 300 degrees).

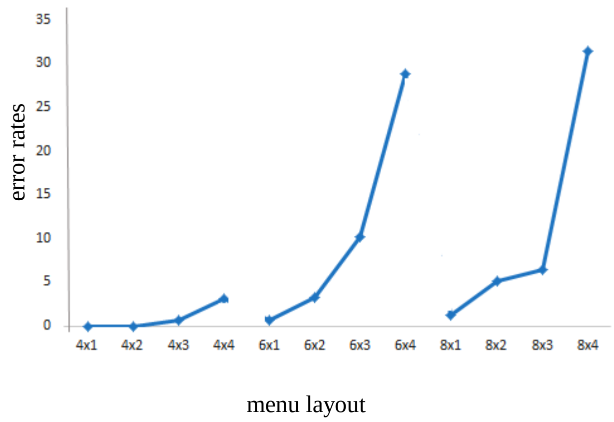

Fig. 2. Percentages of errors in each menu configuration.

Some of the participants reported that left and right directions were easily mistaken. Alerted by the same comment from most of our participants, we performed detail analysis of errors caused by "mental slip". We found that 80% of these errors were made for left and right directions.

Response time was also affected by breadth ($F(2,24)=8.06$, $p<0.05$) and depth ($F(3,36)=151.124$, $p<0.05$). These relationships are shown in Figure 3.

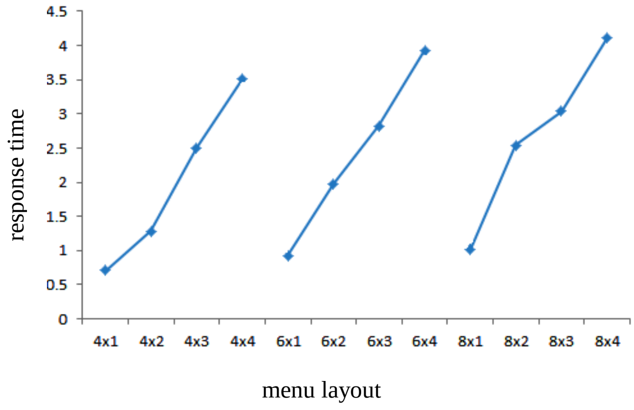

Fig. 3. Response times in each menu configuration.

V. DISCUSSION

Statistical analysis results and qualitative data collected in the study enabled us to answer our research questions relating to the marking gestures of blind people.

1) How many menu items can there be at each level?

From our study and preliminary interviews, we observed that blind people are less aware of directions in term of cardinal directions. On the other hand, they were able to successfully perform marking gestures for every number of menu items (i.e. 4, 6, 8) used in our experiment. This is because we labeled the target directions according to the human body i.e. left, right, upper-right, etc. Thus, in general, we can suggest that blind people are able to perform directional gestures in up to 8 directions which can be labeled related to the human body. When paid close attention to menu selections performed by participants with different extends of sight and time of emergence of blindness, we found no significant differences in performance by the participants. The literature has also reported that, although congenitally blind people had more difficulty in representing spatial information allocentrically, tasks requiring egocentric frames of reference (relating one's body) were similarly performed by early blind, late blind and sighted people [15].

2) How deep or how many hierarchy levels can a blind person can go to perform marking gestures with acceptable error rates?

Our data indicates that the error rate increases linearly with increasing depth. Hence we need to consider what is acceptable regarding error rate. The answer to this question depends on the consequence of the errors. A previous study [21] which was performed with sighted people for pen and mouse interactions recommended using menus with a breadth of 4 up to a depth of 4 (maximum error rate 5.10, SD=4.20) and menus of a breadth of 8 up to a depth of 2 (maximum error rate 8.82, SD=4.62). In our study, the nearest error rates to 8.82 were found when the participants performed gestures for 8-item menus up to a depth of 3 (error rate 6.41, SD=6.93), all of which were error rates less than 10%. Thus, in general, we can suggest that blind people can perform hierarchical marking gestures up to 4 levels in 4-item menus (error rate 3.15, SD=5.28), up to 3 levels for 8-item menus (error rate 6.41, SD=6.93), and up to 2 levels for 6-item menus (error rate 3.20, SD=8.01) with error rates less than 10%. Compared to 8-item menus, 6-item menus exposed the advantage of large target sizes both in terms of error rates and response times up to 2 levels. Error rates dramatically increased up to 10.25 (SD=9.71) in level 3 of 6-item menus. As the menu level increased, more "off-axis" items were included in the combinations resulting in increased error rates. Thus, 6-item menus with 3 levels border on unreliability.

In terms of response time, target selection time took longer in 8-item menus than in 6-item menus because of "cognition time" and "choice time" [14]. A predictive model of menu selection [1] also suggested that the diameter of marks increased as the number of items increased, resulting in longer pointing time. However, the main limiting factor for reliable menu selection would be error rates because response time can be optimized through practice and the number of times a particular configuration of menus is used [1].

Comparing results from our study and those from [21], it is questionable whether blind people have any advantage over sighted people in spatial ability to perform hierarchic marking gestures. We speculated that the difference in performance from our study and [21] is because of the different input modalities. In [21], the participants drew marks on the screen using a pen or a mouse. In our study, the participants performed markings using motion gestures. Physical movement with motion gesture is an expressive channel which has six degree of freedoms such that the directions of movement can be more easily related to the human body applying proprioception. A previous study [24] also demonstrated that interactions took advantage of proprioception over interaction in other forms of interactions.

3) Is breadth better than depth or vice versa?

The quantitative data in our study indicated that blind people made the fewest errors in 4-item menus up to level 4. However, subjective data indicated that blind people preferred fewer levels with more items in each level. When asked their preference among 4x3 and 8x2 or 6x2, most of the participants preferred 8x2 or 6x2. One of the participants stated, "If there are too many levels, I need to reorient the directions and it's tiring." Thus, four-item menus with 4 levels appeared to be "not recommended" despite the low error rates. However, it is reasonable to adjust breadths and depths in these ranges, depending on the purpose of use.

VI. DESIGN GUIDELINES

Throughout the studies, we collected participants' subjective comments about gesture preferences, menu selections and preferable menu layout, etc. Based on comments from the participants, we provided design guidelines for marking menus and motion gestures in mobile interactions.

A. Prferable Gestures

All participants commonly stated that diagonal directions (i.e. upper-left, upper-right, etc.) are difficult to instantly understand. Because all our participants are right-handed, they mentioned that gestures to lower-left and upper-left directions are the most tiring gestures to perform. Thus, designers should avoid those gestures for frequently used functions. The participants also mentioned that downward gestures were particularly easy to perform because they followed the gravity. Regarding "mental slip" errors caused in left and right directions, menus at left and right positions should be designed such that the consequences of operations are close or the consequences of making mistakes are not serious.

B. Menu Layout

Our participants suggested that one motion (i.e. single stroke gesture) were desirable for functions such as answering or declining a call. Also, gesture customization should be supported wherever possible. The subjective comments informed us that end-user customization is particularly desirable for functions such as phone (arranging contact names) and media player (customizing playlists). Although customization can be allowed for menu levels up to the extent of efficiency and comfort with which a blind person can perform (as discussed in earlier section), for menus assigned by designers, menu breadth of 4, 6, 8 with menu depth until 2 would be the most desirable when considering the learnability and memorability of menu layouts for blind users.

C. Menu Learnability

There remains a need to consider the learnability of the entire menu layout in novice mode for non-visual marking menus. One advantage of the traditional marking menu is that it helps users make efficient transitions from novice to expert modes and skill levels because it provides visual information about the entire menu layout in novice mode. For non-visual marking menus, information about the entire menu layout should be provided to users using speech, before the users switch to expert mode. Learnability would be facilitated if menu items were arranged as close as possible to user expectations, e.g., place the most frequently used menus in on-axis positions, and sorting the menus in meaningful way. End user customization of menus would also be helpful for learnability and memorability of menu layouts.

D. Gesture Recognition

We found that the participants had different preferences for movement to select a menu. Movements were different in length and velocity, etc. It was difficult for the system to recognize gestures performed using movement with very low velocity. Gesture recognition should be implemented to allow more freedom of movements of users However, it is not always preferable to have gesture recognition that is too sensitive. Thus, in real applications, it would be a good idea to allow end user customization of thresholds for gesture recognition (e.g. slow movement, small gesture, etc.).

E. Feedback

For successful menu selections, feedback was provided with the menu names read out. Feedback and guidance should also be provided when menu selections are not successful. For example, users may not perform enough movement necessary to select a menu. In that case, vibrations or speech guidance should be issued to notify required actions to the users. Also, it would be desirable to give more options of feedback. Users would prefer a non-verbal sound or a vibration feedback to speech, once they become more expert with the system.

VII. CONCLUSION

This paper investigated the current main problems that blind people are facing using mobile phones. We proposed that marking menus working together with motion gestures can offer more natural and efficient eyes-free interactions on smartphones. Thus, we investigated the extent of efficiency and comfort with which a blind person can perform motion-based marking gestures. Through the study results, we presented the bounds and range of marking gestures that a blind person can perform at each level, and how deep efficient gesture hierarchies can be. Through the qualitative data, we also provided design guidelines for motion-based marking menus on smartphones.

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