"I Don't Want People to Look At Me Differently"

Designing User-Defined Above-the-Neck Gestures for People with Upper Body Motor Impairments

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ABSTRACT

Recent research proposed eyelid gestures for people with upper-body motor impairments (UMI) to interact with smartphones without finger touch. However, such eyelid gestures were designed by researchers. It remains unknown what eyelid gestures people with UMI would want and be able to perform. Moreover, other above-the-neck body parts (e.g., mouth, head) could be used to form more gestures. We conducted a user study in which 17 people with UMI designed above-the-neck gestures for 26 common commands on smartphones. We collected a total of 442 user-defined gestures involving the eyes, the mouth, and the head. Participants were more likely to make gestures with their eyes and preferred gestures that were simple, easy-to-remember, and less likely to draw attention from others. We further conducted a survey (N=24) to validate the usability and acceptance of these user-defined gestures. Results show that user-defined gestures were acceptable to both people with and without motor impairments.

CCS CONCEPTS

• **Human-computer interaction → Empirical studies in accessibility**; **Empirical studies in HCI**.

KEYWORDS

people with motor impairments, above-the-neck gestures, user-defined gestures, gesture elicitation

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1 INTRODUCTION

People with upper body motor impairments have difficulty touching an on-screen target accurately with fingers due to tremors, muscular dystrophy, or loss of arms [22, 32]. They were found to have difficulty entering and correcting texts, grabbing and lifting the phone, making multi-touch input, pressing physical buttons, and so on, especially outside of home [23]. While voice-based interfaces, such as Siri [9], could be an alternative method, they suffer from low input speed and accuracy [9, 23] and may raise privacy and social acceptance concerns when used in public [21, 23].

Recently researchers proposed eyelid gestures for people with motor impairments to subtly interact with mobile devices without finger touch or drawing others' attention [10, 11]. These eyelid gestures, though followed design principles, were created without involving people with motor impairments in the design process. Consequently, it remains questionable whether these gestures are the ones people with motor impairments preferred in the first place. Indeed, the participants with motor impairments in their study [10] also suggested other eyelid gestures and expressed a desire to design *their own* eyelid gestures. Thus, there is a need to involve people with motor impairments to design gestures that will be used by them. In the meantime, prior research demonstrated that allowing users to define their preferred gestures would uncover more representative and preferred gestures [26, 27, 36].

Motivated by this need and prior success of designing user-defined gestures in other contexts, we sought to engage people with motor impairments to design eyelid gestures they prefer. Moreover, as recent research demonstrated the promise of gaze and head pose for hands-free interaction in addition to eyelid gestures [17, 24, 29, 37], we extended the design space of user-defined gestures by inviting people with motor impairments to design *above-the-neck gestures* that include eyelids, gaze, mouth, and head.

We conducted an online user study, in which 17 participants with various upper body motor impairments designed above-the-neck gestures to complete 26 tasks that were commonly performed on mobile devices. These tasks included general commands (e.g., tap and swipe), app-related commands (e.g., open an app or a container with the app), and physical button-related commands (e.g., volume up and down). During the study, participants first watched a video clip explaining each task and its effect on a smartphone and then had time to design and perform an above-the-neck gesture. Afterward, participants rated the goodness, ease, and social acceptance of the gestures they just created. Finally, they were interviewed to provide feedback on the gestures. We collected a total of 442 user-defined gestures. Our results show that participants preferred to use gestures that were simple, easy-to-remember, and less attention-demanding. Based on all the gestures obtained and the rating and frequency of use of each gesture, we assigned each command the most appropriate gesture.

To validate the usability and acceptance of these user-defined gestures, we conducted an online survey that asked participants with and without motor impairments to select the most appropriate gesture from three candidates to complete each of the tasks that were used in the first user study on mobile devices. These candidate options were chosen from the most frequently mentioned gestures from the user study. Results show that our gesture set was well accepted and recognized by people with and without motor impairments though there were some discrepancy. In sum, we make the following contributions in this work:

- We present a set of user-defined above-the-neck gestures based on the gestures designed by people with upper body motor impairments to complete common interactions on mobile devices;
- We show that these user-defined above-the-neck gestures are largely preferred by people with and without motor impairment.

2 BACKGROUND AND RELATED WORKS

Our work is informed by prior work on *interaction techniques for people with motor impairments* and *user-defined gesture designs.*

2.1 Interaction Techniques for People with Motor Impairments

Brain-computer interfaces (BCIs) sense brain signals for people with motor impairments to communicate with the environment or control computer systems without using hands (e.g., [5, 18]). However, BCIs often need long periods of training for users to control their brain rhythms well [25], and people with motor impairments were reported to be concerned about fatigue, concentration, and also social acceptance [4, 30].

Gesture-based interactions have been investigated as an alternative approach. Ascari et al. [3] proposed two machine learning approaches to recognize *hand gestures* for people with motor impairments to interact with computers. However, these approaches are not feasible for people with upper body impairments who could not use their hands freely. To overcome the limitations of body and hand gestures for people with upper body impairments, researchers investigated *eye-based* interactions.

Among all eye-based gestures, *blink* was probably the most widely studied for people with motor impairments. Earlier work used EOG sensors to detect blink to trigger computer commands [14]. The *duration* of blink was also utilized as additional input information. For example, a long blink was detected and used to stop a moving onscreen target [12]. Moreover, blink was also used along with *eye movements* to trigger mouse click [16]. Blink was also used along with the head motion. For example, the frequency of blink combined with *head motion* was used to infer five activities, including reading, talking, watching TV, math problem solving, and sawing [13].

In addition to blink, *wink* was used for people with motor impairments. Shaw et al. constructed a prototype to detect the open and close states of each eye and used such information to infer three simple eyelid gestures: blink, wink the left eye, and wink the right eye [28]. Similarly, Zhang et al. proposed an approach to combine blinks and winks with gaze direction to type characters [38]. Recently, Fan et al. took a step further to investigate the design space of *eyelid gestures* and proposed an algorithm to detect nine eyelid gestures on smartphones for people with motor impairments [10, 20]. These eyelid gestures were designed based on eyelid states, in which two eyelids could be in, and the possible parameters that humans can control, such as the duration of closing or opening an eyelid and the sequence. Although the design of eyelid gestures followed a set of design principles, these gestures were designed by the researchers who did not have motor impairments themselves, and the design process did not involve people with motor impairments in the loop. Consequently, it remains unknown *whether these eyelid gestures were the ones that people with motor impairments preferred in the first place.* In fact, participants with motor impairments in their study could not perform some eyelid gestures well, proposed new eyelid gestures, and expressed the desire to design their own gestures. Motivated by this need, we seek to explore user-defined eyelid gestures that people with motor impairments would want to create and use.

Other body parts, such as the head, have also been used to extend the interaction for people with motor impairments. Kyto et al. [17] compared eyes and head-based interaction techniques for wearable AR and found that the head-based interactions caused less error than eye-based ones. Furthermore, they found the combination of eye and head resulted in a faster selection speed. Sidenmark and Gellersen [29] studied the coordination of eye gaze and head movement and found this approach was preferred by the majority of the participants because they felt better in control and less distracted. Similarly, gaze and head turn were combined to facilitate the control of onscreen targets [24]. Inspired by this line of work that shows the advantage of combining head motion with eye motions, we extend our exploration to include above-the-neck body parts, including both eyes, head and mouth, to allow people with motor impairments to better design a richer set of user-defined gestures.

2.2 User-Defined Gesture Designs

User-defined gestures have been investigated by researchers in various contexts [7, 8, 15, 19, 26, 27, 31, 34, 36]. Wobbrock et al. [36] studied user-defined gestures for multi-touch surface computing, such as tabletop. They investigated the kind of hand gestures non-technical users would like to create and use by asking the participants to create gestures for 27 referents with one hand or two hands. Wobbrock et al. [36] also designed gestures for the 27 referents on their own and compared the gestures created by them with the ones created by the users. They found that they created far fewer gestures than the users, and many of the gestures they created were never tried by users. Kurdyukova et al. [15] studied the user-defined iPad gestures to transfer data between two displays, including multi-touch gestures, spatial gestures, and direct contact gestures. Piumsomboon et al. [26] worked on user-defined gestures for AR and asked people to perform hand gestures with a tabletop AR setting while Lee et al. [19]utilized an augmented virtual mirror interface as a public information display. Dong et al. [7, 8] worked on the user-defined surface and motion gestures for mobile AR applications. In the work of Ruiz et al. [27], they utilized the user-defined method to develop the motion gesture set for mobile interaction. Weidner and Broll [34] proposed user-defined hand gestures for interacting with in-car user interfaces, and Troiano et al. [31] presented gestures for interacting with elastic and deformable displays. These user-defined methods motivated our research. Specifically, our research adopts a similar user-centered approach by investigating what upper-neck gestures people with motor impairments would like to create and how they would want to use such gestures to accomplish tasks on their touch-screen mobile devices.

3 METHOD

The goal of this IRB-approved study was to gather user-defined above-the-neck gestures for common tasks on mobile devices from and for people with motor impairments and then identify the common user-defined gestures they would like to perform to complete each task.

3.1 Participants

We recruited seventeen (N=17) participants through online contact with a disability organization. Table 1 shows the demographic information. Twelve were males and five were females. Their average age was 29 years old (SD = 6). All participants had some forms of motor impairments that affected their use of mobile phones. Ten participants had arm or hand problems. Specifically, eight had the loss or injury of their limbs, six had cerebral palsy who had shaky hands and difficulty controlling their hand movements. The remaining three had spinal cord injuries, two of whom needed to use a wheelchair, and one did not have hand sensation. Seven had their legs amputated and needed prosthetics or crutches. Some of them had difficulties speaking clearly or fluently due to the influence of cerebral palsy, but it did not affect our user study. None of them used upper-neck gestures to control devices prior to the study. The participants were compensated $15 for the study.

Table 1: Participants' demographic information

ID	Age	Sex	Motor impairments
1	32	M	Spinal cord injuries, wheelchair user
2	25	M	Cerebral palsy, shaking hands and hard to control hand movements
3	30	M	Loss or injury of limbs loss of both of arms
4	19	F	Cerebral palsy, shaking hands and hard to control hand movements
5	28	M	Loss or injury of limbs, loss of right leg, needs prosthetics
6	31	F	Cerebral palsy, shaking hands and hard to control hand movements
7	21	M	Cerebral palsy, shaking hands and hard to control hand movements
8	32	F	Spinal cord injuries, wheelchair user
9	42	M	Cerebral palsy, shaking hands and hard to control hand movements
10	34	M	Loss or injury of limbs, loss of one leg, needs crutches
11	35	M	Spinal cord injuries, hands have no feeling
12	26	M	Loss or injury of limbs, right hand has no fingers
13	28	M	Cerebral palsy, shaking hands and hard to control hand movements
14	26	F	Loss or injury of limbs, loss of left leg, needs crutches
15	35	M	Loss or injury of limbs, loss of both of arms
16	24	M	Loss or injury of limbs, loss of legs, needs crutches and prosthetics
17	27	F	Loss or injury of limbs, missing fingers on left hand

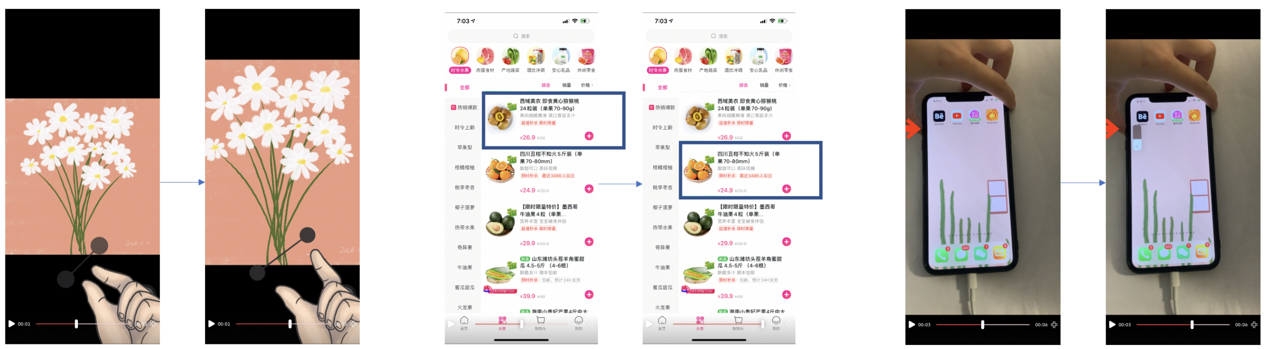
3.2 Tasks

Firstly, we studied the instructions on the official websites of iOS and Android [1] to learn about the commands and corresponding gestures designed for touchscreen smartphones. Moreover, we drew inspiration from recent work [10, 11] for the commands that were controlled by eyelid gestures designed for people with motor impairments. In the end, we identified 26 commands commonly used for smartphone interactions. Based on their similarities, we clustered these commands into three groups. *Group 1* included twelve **General commands**, which were Single Tap, Double Tap, Flick, Long Press, Scroll Up, Scroll Down, Swipe Left, Swipe Right, Zoom In, Zoom Out, Drag, and Rotate. *Group 2* included ten **App-related commands**, which were Open the App, Move to Next Screen, Next Button, Previous Button, Open the Container (a UI component within an app), Next Container, Previous Container, Move to Next Target App, Open Previous App in the Background, Open Next App in the Background. *Group 3* included four **Physical Button-related commands**, which were Volume Up, Volume Down, and Screenshot.

The general commands were obtained from mobile phone systems (iOS & Android), and the app-related commands were inspired by a recent study [10], which proposed commands such as switching between apps, switching between tabs in an app, and switching between containers in a tab. The four physical button-based commands were inspired by the commands supported by iOS and Android, such as turning the volume up & down, taking screenshots, and locking the screen.

[1]https://support.apple.com/en-us/guide/iphone/iph75e97af9b/ios, https://support.apple.com/en-us/guide/iphone/iphfdf164cac/ios, https://support.apple.com/en-us/guide/iphone/iphca3d8b4e3/ios, https://support.google.com/android/answer/9079644?hl=en, https://support.google.com/android/answer/9079646

Figure 1: The study procedure.



(a) Zoom In

(b) Next Container

(c) Volume Up

Figure 2: Video clips: (a) is the video clip for Zoom In, which is an example of enlarging a picture by hand interaction, (b) is the video clip for the Next Container command in the App-related group, showing the target containers that the participants needed to interact with, (c) is the video clip for the Volume Up command in the button-related group, which shows how one of the authors interacted with her mobile phone to increase the volume.

3.3 Procedure

Figure 1 shows the study procedure. After answering the background questionnaire, participants were asked to watch a short video clip for a command. We created a short video clip to show each command and its effect on a smartphone.

Figure 2 shows example video clip frames for the command Zoom In, Next Container, and Volume Up. Showing video clips instead of explaining verbally was to ensure the consistent presentation of tasks to participants. After watching the video clip, participants would create an above-the-neck gesture for it and perform the gesture to the moderator.

To reduce any ordering effects, the task videos for the general commands and physical button-related commands were presented to participants in random order. Because there was a logical order among the commands in the app-related group, we kept the order of the tasks in this group to avoid confusions. During this process, we asked participants to think aloud so that the moderator could better monitor the design process. After performing the user-defined gesture, they were asked to rate the goodness, ease, and social acceptance of the gesture for the command using 7-point like-scale questions. Then, participants repeated this process until they created gestures for all commands.

To reduce the gesture conflicts happening during the study, we asked participants to design different gestures for each command within the same group (i.e., three groups for the general, app-related, and physical-button related commands). As for the commands that were not in the same group, we allowed the participants to perform the same gesture. However, due to a large number of commands, some participants might forget their previous gestures. Thus, the moderator monitored the gestures already created, and if she found a conflict gesture was proposed, she would remind the participants to change to a different gesture for either the current one or the earlier one that was conflicted with. In addition, participants were allowed to change their minds if they later wanted to go back and change a previous one.

All study sessions were conducted remotely through a video conference platform in order to comply with the COVID-19 social distance requirements, and the whole process was video recorded. In total, we collected 442 user-defined above-the-neck gestures (17 participants x 26 commands).

3.4 Conceptual Complexity of the Commands

Before we determined the final user-defined gestures for the commands, we took a step to understand the perceived complexity of the commands. To do so, we calculated the **conceptual complexity** of each command. Conceptual complexity of a command was a concept widely used in prior works (e.g., Wobbrock et al.'s work [36], Arefin Shimo et al.'s work [2], and Dingler et al.'s work [6]), which

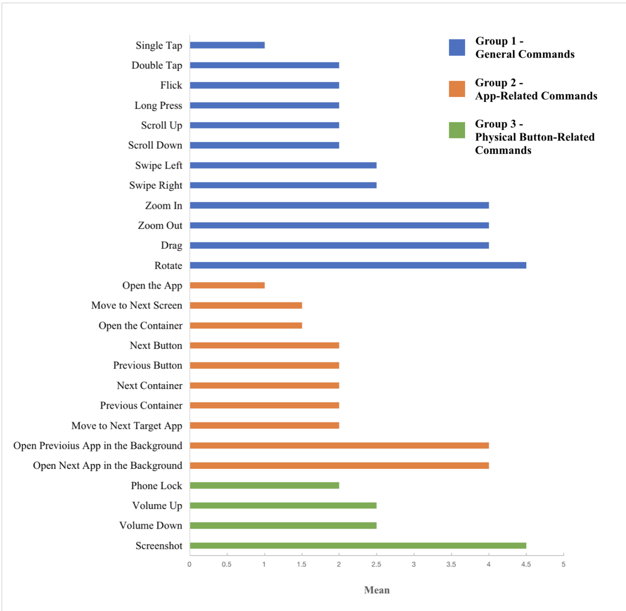


Figure 3: The conceptual complexity of 26 commands, rated by two HCI researchers. The higher the score, the more complex the command perceived by the researchers.

measures the perceived difficulty of the command from HCI researchers' points of view. For example, Scroll Up and Scroll Down (e.g., scrolling up to the next page and scrolling down to the previous page) are commands that we, as HCI researchers, believed could be achieved easily with one finger and thus has a low conceptual complexity. In contrast, Zoom In and Zoom Out (e.g., zooming in to enlarge the photo and zooming out to shrink the photo) require more than one finger (e.g., spreading two fingers outward to zoom in and bringing two fingers inward to zoom out) or more than one tap (e.g., double tap), so it has a relatively higher conceptual complexity.

To determine the conceptual complexity for each command, two HCI researchers rated the difficulty of completing each command on a 5-point Likert scale (1: the relatively easiest, 5: the relatively most difficult) independently to avoid influencing the other person's point of view. A score of 5 means that it was perceived by the researcher as the most difficult among the 26 commands. The scores of the two researchers were similar for most commands with only a few that had relatively bigger differences. Finally, we calculated the average of the scores assigned by the two researchers to get the conceptual complexity of the command. Figure 3 shows the conceptual complexity for each command.

4 RESULTS

We followed the analysis methods of prior user-defined gesture design papers (e.g., [36]) to obtained *the gesture taxonomy*, the *gesture agreement score*, the *participants' ratings of the gestures performed*, and the final *user-defined gesture set*. We also analyzed the participants' interviews to understand the design rationales.

4.1 User-defined Above-the-Neck Gestures Taxonomy

Table 2: The seven categories of the user-defined above-the-neck gestures, including only eyes, only head, only mouth, eyes and head, eyes and mouth, head and mouth, and eyes, head and mouth, and the gestures within each category

Taxonomy of All Gestures	Breakdown of Each Taxonomy
Only Eyes	blink
	gaze
	eye-movement
	eye size
	eyebrows
	blink + gaze
	gaze + eye size
	eye movement + eye size
	blink + eye movement
	gaze + eye movement
	blink + gaze + eye movement
	blink + eye size
Only Head	head movement
	head distance
	head rotation
	head distance + head movement
Only Mouth	pout
	wide open then close mouth
	wry mouth
	suck mouth
	smile
Eyes & Head	blink + head movement
	eye size + head movement
	eye gaze + head movement
	eye movement + head movement
	gaze + head distance
	gaze + head rotation
	gaze + eye size + head movement
Eyes & Mouth	blink + pout
	blink + wide open mouth
Head & Mouth	head movement + pout
	head movement + wide open then close mouth
Eyes & Head & Mouth	eye movement + head movement + wide open mouth

We collected 17×26=442 gestures for all 26 commands and classified them according to different body parts involved (i.e., the eyes, the head, and the mouth).

Gesture Categories. We grouped the gestures into **seven categories** based on the body parts involved. These seven categories included *a single body part* and *the combinations of different body parts*: **only eyes**, **only head**, **only mouth**, **eyes & & head**, **eyes & & mouth**, **head & & mouth**, and **eyes & & head & mouth**. For each dimension, we subdivided it according to the gestures that the participants performed. Table 2 shows the taxonomy of the user-defined above-the-neck gestures.

The *only eyes* category includes five basic types of eye gestures: *blink*, *gaze*, *eye movement*, *eye size*, *eyebrow* and the combination of these basic eye gestures. Blinks include single and double blinks, as well as different numbers of blinks. Gaze is the eyes on the screen, which may differ in the length of time. Eye movement includes moving the eyes up and down, left and right, eye rotating and cross-eye.. Eye size includes wide opening, closing, and squinting actions. Eyebrow includes squeezing eyebrows. After combining two or more of these single eye movements, there will be dozens of combinations in total. We got rid of the ones that the participants did not perform and ended up with seven combinations of eye gestures.

The *only head* category includes *head movement*, *head distance*, *head rotation*, and the combination of different head gestures as well. The scope of head movement is turning and tilting the head in different directions. We separated head rotation from the head movement because the amplitude of the rotation is larger and more apparent. In addition, the tilted head included in the head movement is a bit similar to the half-circle rotation, so we thought that distinguishing them could help better understand the participants' preference for these two different amplitude gestures. Head distance means the distance between the head and the mobile phone screen that people would move heads closer or further from the screen. Among all the combination possibilities of these single head gestures, only the combination of head movement with head distance change was chosen by our participants.

The *only mouth* category includes *pout*, *open mouth*, *close mouth*, *wry mouth*, *suck mouth*, and *smile*.

Combined Gestures. The above three categories are the gestures involving an individual body part. The participants also made some *combined gestures*, which were the gestures with a combination of different body parts. One of the most frequently proposed combined gestures is *the combination of eyes and head gestures*, such as blinking followed by a nod, closing the eyes with the head swinging, gazing with head rotation, etc. The combination of eyes & mouth and the combination of head & mouth had two different varieties in each category. The eyes & head & mouth had only one combination.

Distribution of Gesture Groups. There were many overlaps between the gestures designed by different participants. After removing overlaps, we found 250 unique user-defined above-the-neck gestures. Among these unique gestures, 44.4% were only-eye gestures, 14.8% were only-head gestures, 4.8% were only-mouth gestures, 30.8% were eyes & head, 1.2% were eyes & mouth, 3.2% were head & mouth, and 0.8% were eyes & head & mouth. This finding suggests that although participants could use the mouth, the eyes, and the head, they still preferred eye-based gestures the most followed by eyes & head gestures and then the only-head gestures.

Among all categories, the *Only Eyes* category was most diverse. Moreover, the combinations including eyes (e.g., Eyes & Head, Eyes & Mouth) were more common than those performed by other parts (e.g., Head & Mouth).

4.2 Determination of the User-defined Gesture Set for the Commands

To derive the final user-defined gesture set from all gestures proposed by all participants, we collated the gestures included in each command and counted the number of participants performing the same gesture. We resolved conflicts between gestures to obtain the final gesture set. We also calculated the **agreement score** for each command. Agreement score was initially proposed by Wobbrock et al. [35] and later widely used in studies uncovering user-defined gestures for various platforms (e.g., tabletop, phone, watch, and glasses [2, 6, 27, 33, 36]. It intuitively characterizes differences in agreement between target users for assigning a gesture to a given command. In general, the higher the agreement score of a command, the better the participants are in agreement with the gesture assigned to the command.

4.2.1 Agreement Score. We categorized the gestures performed by the participants for each command and then counted how many people made the same gesture. These groups and the number of people in each group were used to calculate the **agreement score** of the commands. We adopted this method from prior user-defined gesture research [27, 35, 36] and used the following equation:

$$A_c = \sum_{P_i} (\frac{P_i}{P_c})^2 \tag{1}$$

In Equation.1, c is one of the commands, A_c represents its *agreement score* based on participants' proposed gestures for this command. The value ranges from 0 to 1. P_c is the total number of gestures proposed for c, which is the number of participants in our case (N=17). i represents a unique gesture. Because different participants proposed the same gestures, the number of *unique gestures* was smaller than the total number of proposed gestures. P_i represents the number of participants who propose the unique gesture i. Take the *Single Tap* command as an example, 17 participants proposed 17 gestures in total, thus Pc equals 17. Among these gestures, there were seven unique gestures. There were 7, 4, 2, 1, 1, 1, and 1 participants who proposed each of the seven unique gestures respectively. As a result, the agreement score of the Single Tap command was calculated as follows:

$$(\frac{7}{17})^2 + (\frac{4}{17})^2 + (\frac{2}{17})^2 + 4(\frac{1}{17})^2 = 0.25 \tag{2}$$

.

Figure 4 shows the agreement score of the gestures proposed for each command. The commands were arranged in the same order as the conceptual complexity as in Figure 3. In general, the higher the agreement score, the higher the participants' consensus on which gesture(s) should be assigned. The agreement score of *Double Tap* was high, which indicated that participants more agreed on which gesture(s) should be allocated to this command. In contrast, the agreement score of *Rotate* was relatively lower, which indicated that participants proposed more diverse gestures for it and less agreed on which gesture should be allocated to it.

4.2.2 Conceptual Complexity vs. Agreement Score. As we explained in Sec.3.4, the *conceptual complexity* is a measurement of the perceived complexity of commands from **researchers' perspectives**. In contrast, *agreement score* is a measure of perceived complexity

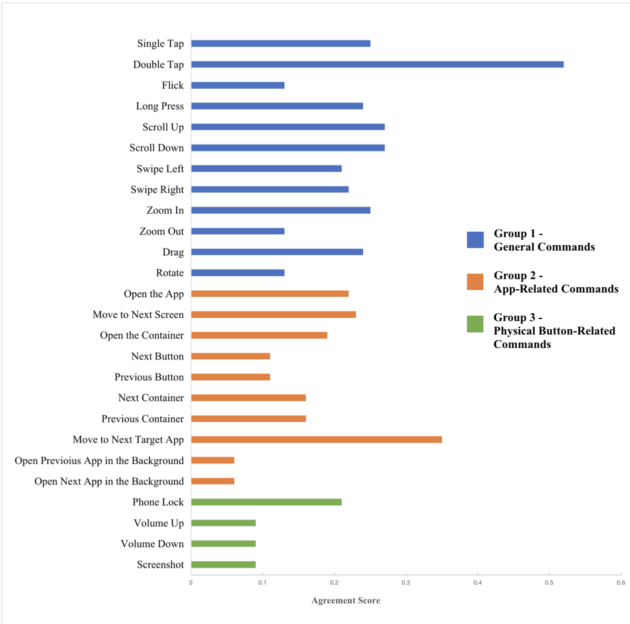


Figure 4: The *agreement scores* of the 26 commands. The higher the score, the higher the participants' consensus on which gesture(s) should be assigned

of commands from **end-users' perspectives**. If the perception of researchers aligns with the perception of end-users (i.e., people with motor impairments), then we should expect to see a correlation between the two measures. We did Pearson Correlation Test and found no significant correlation between the agreement score and conceptual complexity score of each command (r=-.38, p=.05). In other words, the commands given a low conceptual complexity score by the researchers did not result in a high agreement score. This suggests that there was a discrepancy between the researchers' understanding of the complexity of the commands and gestures and that of the target users'. This finding further highlights the necessity to involve end-users into the design process to design user-defined gestures that they, instead of researchers, would perceive easy-to-use.

4.2.3 Gesture Conflict. We found that in some cases participants proposed different gestures for a command. Thus, we needed to resolve the conflicts to assign one gesture for each command.

Our conflict resolution strategy was as follows. When the same gesture was allocated to both a single command (e.g., Drag) and a paired commands (e.g., Swipe Left & Swipe Right), we would prioritize the gesture to the paired ones because the cost for finding alternative gestures for the paired commands was higher than that for a single command. After allocating the conflicted gesture to the paired commands, we allocated the gesture proposed by the second-highest number of participants for this single command to it. Figure 5 illustrates the process with an example. The same gesture "Turn Head to the Left and Look Left" was proposed by the same number of participants (N=6) for both the single command (i.e., Drag) and the paired commands (i.e., Swipe Left & Swipe Right). Our resolving strategy would assign this gesture to the Swipe Left command. Next, we allocated the gesture proposed by the second-highest number of participants to the Drag command. In this case, it was "Gaze, and Look At a Certain Direction."

4.2.4 Final User-defined Above-the-Neck Gesture Set for the Commands. Table 3 shows the final gestures for each command. Most of the commands have only one allocated user-defined gesture (i.e., Gesture 1 in the table). However, there are three commands that had more than one gesture allocated. This is because these commands have more than one gesture proposed by the same number of participants. As shown in Table 3, twenty-three commands were assigned with one gesture, two commands with two gestures, and one command with three gestures.

Figure 6 further illustrates the final user-defined above-the-neck gestures for the 26 commands. There were 30 gestures in the final gesture set. 20 were only-eyes gestures, 3 were only-head gestures, and 7 were eyes & head gestures.

We found continuity in the mappings between he final gesture set and the commands. When two commands were related, such as single tap and double tap, the final assigned gestures were blinking once and blinking twice, which were strongly correlated. Mappings between gestures and commands also showed symmetry. For example, for swipe left/right, the gestures were looking left/right and turning head to the left/right; and for zoom in and zoom out, the gestures were wide-open eyes and squint eyes. Mappings were also logical, such as the phone lock was closing eyes.

4.2.5 Subjective Ratings of the Gestures. We asked participants to rate the goodness, ease of use, and social acceptance of each gesture they performed. We divided the gestures under each command into large groups and small groups. The large group was defined as the number of people making that gesture over the number of people making the other gestures, and it was usually the gesture that was selected in the gesture set. The rest are the small groups. We compared the participants' average goodness (mean of large groups=5.94, mean of small groups=5.94), ease of use (mean of large groups=5.80, mean of small groups=5.72), and social acceptance (mean of large groups=5.69, mean of small groups=5.70) of the gestures in large groups with those in small groups. There was no significant difference between them. We did Pearson Correlation Test and found that the conceptual complexity of the commands did not have a strong correlation of their goodness (r=-.42, p=.04), ease of use (r=-.20, p=.34), or social acceptance (r=-.40, p=.05).

4.3 Perceptions of the User-defined Gestures

We present the following insights learned from participants' feedback about user-defined gestures.

4.3.1 Easy to Use and Understand. After participants made a gesture, we asked them why they chose that gesture, the most common feedback was that it was simple to understand and easy to perform. P13 explained, *"Because I feel that these gestures are good, simple, easy to perform, so I choose them."*, and P16 argued, *"It is easy to understand and belongs to the normal range of head movement."*

The user-defined gestures also resembled common touch gestures on smartphones. Many participants thought about creating gestures to complete commands in conjunction with how they

Commands	Gesture 1	No. of participants	Gesture 2	No. of participants
Drag	Turn Head to the Left and Look Left	#6（P3，6，8，9，12，16）	Gaze, and Look at a Certain Direction	#3（P1，4，5）
Swipe Left	Turn Head to the Left and Look Left	#6（P1，2，5，7，10，14）		
Swipe Right	Turn Head to the Right and Look Right	#6（P1，2，5，7，10，14）		

Figure 5: Gesture conflict 1: a single command (e.g., Drag) conflicted with paired commands (e.g., Swipe Left & Swipe Right). In this case, we assigned gesture 2 to Drag and gesture 1 to Swipe Left & Swipe Right. The column of No.of participants means how many participants performed the same gesture, including the participant number. The gestures were arranged in the descending order of No.of participants.

Table 3: The final user-defined gestures for all commands. Most commands have one allocated gesture (i.e., Gesture 1) and a few have two or three gestures (i.e., Gesture 2 and Gesture 3)

Commands	Gesture 1	Gesture 2	Gesture 3
Single Tap	eyes blink once		
Open the App	eyes blink once		
Move to Next Screen	turn head to the left and look left		
Open the Container	eyes blink once		
Double Tap	eyes blink twice		
Flick	raise head		
Long Press	gaze for 3-5s		
Next Button	look right, then blink once		
Previous Button	look left, then blink once		
Next Container	look downward		
Previous Container	look upward		
Move to Next Target App	look right		
Scroll Up	raise head and look upward	look upward	
Scroll Down	lower head and look downward	look downward	
Phone Lock	close eyes for 3s		
Swipe Left	turn head to the left and look left		
Swipe Right	turn head to the right and look right		
Volume Up	blink right eye		
Volume Down	blink left eye		
Zoom In	wide open eyes		
Zoom Out	squint eyes		
Drag	gaze, and look at a certain direction		
Open Previous App in the Background	raise head, then turn head to the right, then blink eyes		
Open Next App in the Background	raise head, then turn head to the left, then blink eyes		
Screenshot	eyes blink three times		
Rotate	turn head to the left, and look at the screen	eyes look counter-clockwise	tilt head

would use their smartphones with hands. For example, when being asked to swipe to the next page, many participants turned their heads to the left because they also swiped to the left if they had to use their hands. P11 used his computer more often than his phone, so he considered his habits of using the computer when creating gestures. For example, when doing the single tap command, he blinked his left eye and said, *"Operation is similar to clicking with the left mouse button"-P11.* Using different mobile phone models also affected the gestures. Many Android phone users chose to blink three times when taking a screenshot because they usually used three fingers to pull down for taking a screenshot with their Android phones, so this gesture was better for them to understand. However, as iOS uses a different gesture for screenshot, this gesture might not be easy to understand for iOS users.

4.3.2 Memorability. During the study, some participants mentioned that they forgot what gestures they had proposed earlier. When P14 was doing command 15, she said she couldn't remember

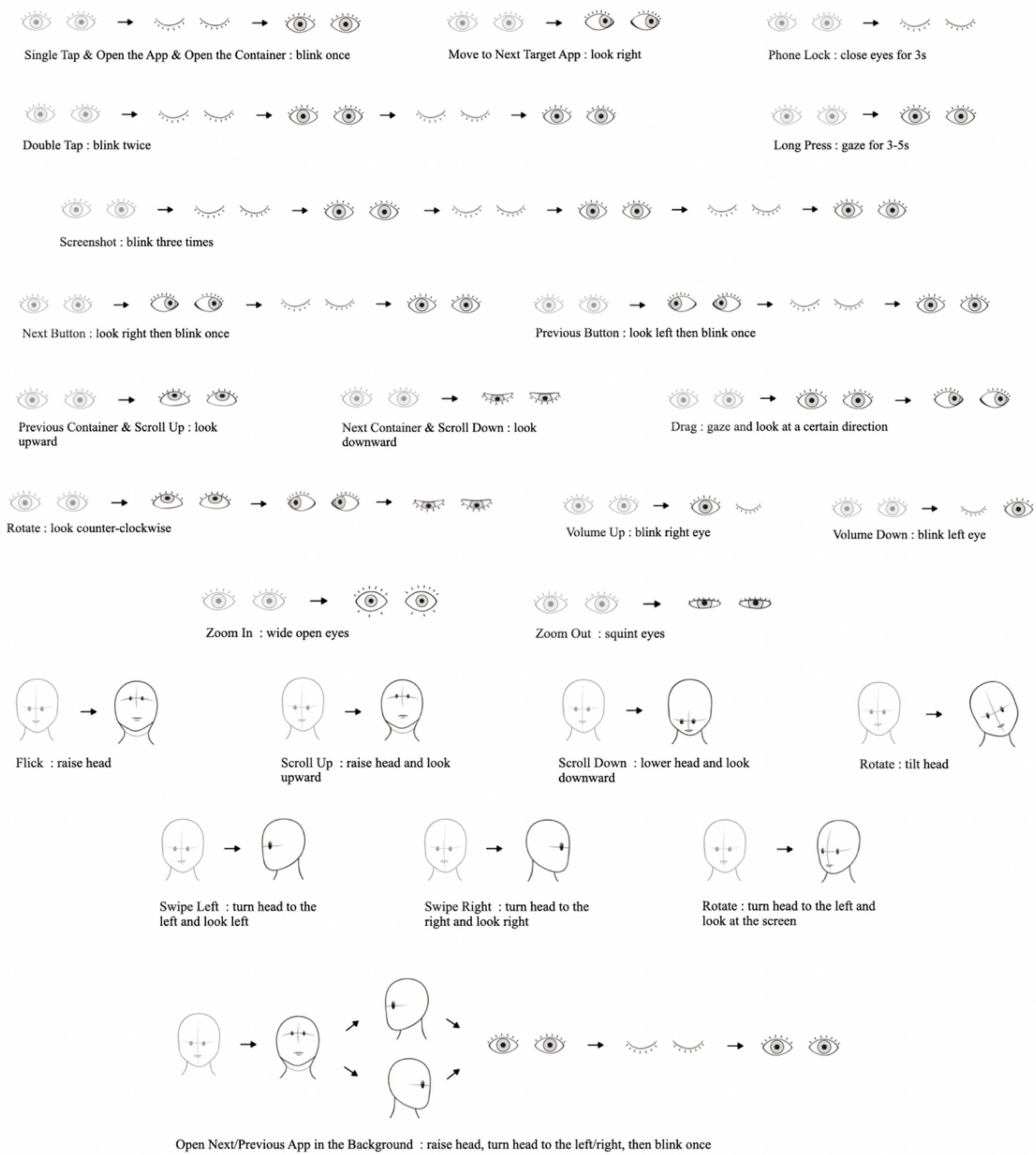


Figure 6: Visual illustrations of the final user-defined above-the-neck gestures for the 26 commands.

what gestures she had done. To address this issue, many participants deliberately chose to make the gestures they could easily remember.

4.3.3 Duration of Gestures. There were some gaze or close-eyes gestures, and these gestures would need to take into account the issue of how long the eyes were gazed at or closed. Although some participants mentioned 5 seconds or 10 seconds, most were 2 seconds or 3 seconds. *"Would 2 seconds or 3 seconds be better? It is clearer to stop for 3 seconds."-P8*; *"It would be inconvenient if closing the eyes for too long."-P12*

4.3.4 Recognition. Many participants considered whether the gesture would be too subtle for the phone to recognize when they did it. For example, when considering the gaze time, the participants thought about whether the time was too short for the phone to notice. Many participants preferred head gestures because they thought eye movements were too small to be identified. They also considered whether the gesture was confused with our natural or spontaneous movements which might accidentally trigger a command. Thus, some participants made a distinction between the gestures they performed and what we usually did spontaneously. *"I feel that the head forward may not be very sensitive to identify."-P14*; *"An occasional small action may affect the phone recognition."-P11*

4.3.5 Self-condition. Participants mentioned that their motor impairments could cause some eye or facial movement difficulties, especially eye closure difficulties. Some participants had difficulty closing a single eye, so they chose to make the gestures in both eyes together. Some participants had difficulty closing the left or right eye, and they chose to make the gesture with the eye that had no difficulty closing. *"I can close both eyes, but cannot close only one eye, so I do it with both eyes."-P13* Similarly, P3 was left-handed and preferred to use his left eye to make gestures.

4.3.6 Social Acceptance. Participants were very concerned about the perceptions of others when designing the gestures. They would consider whether the gestures were too exaggerated because they did not want to attract attention from others. They would like to choose some simple gestures so that they would not look strange. *"Doing eye gestures will still take into account the feelings of others."-P3*; *"Simple, does not attract special attention or disturb others."-P11*; *"I don't want people to look at me differently."-P14*

5 SURVEY STUDY

We identified user-defined above-the-neck gestures by resolving conflicts in the original gestures created by a group of 17 people with motor impairments as illustrated in the previous section. One follow-up question would be: **what are the more appropriate gestures among these user-defined ones for the users who would use the gestures to interact with smartphones**? Our gesture elicitation study was to create a gesture set for people with motor impairments to interact with the touchscreen smartphones without touch. However, able-bodied people might also encounter the same difficulties in many scenarios and find such gestures useful. For example, it would be hard to operate the phone by hand when people's hands are occupied, for example, while carrying bags or with wet or dirty hands. As a result, we included people without motor impairments in this survey study as well to understand their preferences for the user-defined gestures designed by people with motor impairments. To answer this question, we conducted an online survey to validate the agreement of the user-defined gesture set by people with and without motor impairments.

5.1 Method

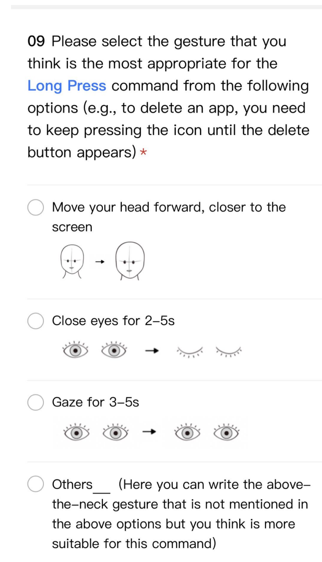


Figure 7: Survey example: the screenshot of the Long Press question.

In the survey, participants were first asked about basic demographic info. For each of the 26 commands used in the previous gesture elicitation study, participants chose the most appropriate gesture from three candidate options. These candidate options were the most frequently performed gestures for each command from the previous study and were arranged in random order to reduce potential order effect. We also provided an additional option for participants to write out what they thought was most appropriate if they felt none of the three options were suitable.

Figure 7 shows the screenshot of the question for the Long Press command in the survey. The survey was published in an online format and took an average of 5 minutes to complete.

5.2 Participants

Twenty-four uncompensated volunteers participated in the survey study, including 10 people with motor impairments and 14 people without motor impairments. Ideally, it would be best to recruit people with motor impairments who do not have any prior knowledge about the study. However, due to the difficulty in recruiting people with motor impairments during the pandemic, we recruited the 10 participants with motor impairments who took the previous gesture elicitation study. To mitigate the potential memory effect, we did intentionally conduct the survey study one month after the gesture elicitation study. With a one-month time gap between the two studies, it was unlikely that these participants would still

	Participants With Motor Impairments				Participants Without Motor Impairments				Consistency
	Gesture1	Gesture2	Gesture3	Others	Gesture1	Gesture2	Gesture3	Others	
Single Tap	60%	30%	10%	0%	43%	57%	0%	0%	
Double Tap	40%	40%	20%	0%	50%	43%	7%	0%	●
Flick	60%	30%	10%	0%	57%	14%	21%	7%	●
Long Press	20%	50%	30%	0%	14%	29%	50%	7%	
Scroll Up	40%	40%	20%	0%	36%	14%	50%	0%	
Scroll Down	50%	30%	20%	0%	36%	21%	43%	0%	
Swipe Left	30%	60%	10%	0%	29%	57%	14%	0%	●
Swipe Right	40%	40%	20%	0%	36%	50%	14%	0%	●
Zoom In	50%	30%	20%	0%	50%	14%	36%	0%	●
Zoom Out	70%	20%	10%	0%	79%	7%	14%	0%	●
Drag	70%	10%	20%	0%	43%	7%	50%	0%	
Rotate	60%	20%	20%	0%	50%	14%	36%	0%	●
Open the App	40%	30%	30%	0%	57%	36%	7%	0%	●
Move to Next Screen	50%	30%	20%	0%	43%	14%	43%	0%	●
Open the Container	30%	30%	40%	0%	36%	29%	29%	7%	
Next Button	30%	30%	40%	0%	64%	14%	14%	7%	
Previous Button	0%	60%	40%	0%	57%	21%	14%	7%	
Next Container	30%	30%	40%	0%	36%	21%	36%	7%	●
Previous Container	20%	60%	20%	0%	21%	29%	43%	7%	
Move to Next Target App	30%	40%	30%	0%	21%	36%	36%	7%	●
Open Previous App in the Background	50%	20%	30%	0%	50%	14%	21%	14%	●
Open Next App in the Background	30%	30%	40%	0%	43%	7%	36%	14%	
Phone Lock	50%	30%	20%	0%	64%	7%	29%	0%	●
Volume Up	30%	50%	20%	0%	21%	43%	29%	7%	●
Volume Down	30%	40%	30%	0%	29%	36%	29%	7%	●
Screenshot	40%	30%	30%	0%	79%	7%	14%	0%	●

Figure 8: Survey results: participants with motor impairments in green color, participants without motor impairments in orange color. The darkest green/orange color represents the gestures with the highest number of selections for that command. The lightest green/orange color represents the gesture with the lowest number of selections. The black dots in the consistency column represent the two groups of people making the same choices.

remember the commands or how they assigned the gestures to the commands a month ago. For the 14 participants without motor impairments, we recruited them through both online and offline means. The average age of all participants was 29 years (*SD* = 3).

5.3 Results

In Figure 8, we showed the results of the participants with motor impairments in green color and the results of the participants without motor impairments in orange color. The three gesture options in all questions were collectively referred to as *Gesture 1*, *Gesture 2*, and *Gesture 3*, in descending order of the number of times participants performed them in the previous gesture elicitation study. Of the results for all participants in the survey study, *Gesture 1* was the first choice for 17 out of 26 commands and the second choice for the other 6 commands. From the results of the ten motor-impaired individuals, *Gesture1* was preferred in 15 commands and the second choice for 9 commands. From the results of fourteen non-motor-impaired individuals, *Gesture1* was the first choice for 15 commands and the second choice for 8 commands. Furthermore, Figure 8 also includes a "consistency" column to indicate the commands for which both participants without and with motor impairments agreed on the most popular gesture options. Out of the 26 commands, both user groups agreed on 16 commands (62%), which indicates that our gesture set had a reasonably high agreement between participants with and without motor impairments.

The agreement of *Gesture 1* by the motor-impaired population was most on general commands, and the non-motor-impaired population was most on app-related and button commands. A possible reason for this might be that as the complexity of the command increased, the gestures became more complex, and the different above-the-neck parts involved in the gestures also increased correspondingly. Some app-related commands were more complicated than general commands. Thus, participants were more likely to create complex gestures for them. For participants with motor impairments, in addition to considering the appropriateness of the gestures, they might have also considered their personal physical conditions assigning gestures to commands, making it more difficult to reach an agreement.

We also noticed that none of the people with motor impairments chose *Others* options in the survey. One possible reason might be that they had already done the earlier user study. Therefore, the three options provided were either the same or similar to what they had already demonstrated in the previous gesture elicitation study, which led to their agreement on these three options. While in the survey for non-motor-impaired participants, we found that one participant chose the option *Others* very frequently. We checked her responses and found that she indicated that she did not come up with more appropriate gestures but disagreed with our provided options. We then interviewed her briefly, and she explained, *"some gestures are so complicated that no one would find it easier than using their hands unless they had paraplegia"*. Another participant also chose *Others* options for two of the commands, but did not suggest any gestures she would prefer to use. In sum, although there were some disagreements between participants without and without motor impairments, participants without motor impairments still mostly preferred one of the three gestures derived from the previous gesture elicitation study than proposing their own gestures.

Through the survey, we found that the choices of gestures by people with and without motor impairment were mostly consistent with our gesture set. However, there were also some differences due to differences in their physical conditions or the lack of understanding of people with motor impairments by people without motor impairments. In general, our gesture set is reasonably applicable to people with and without motor impairments and is accepted and recognized by the public.

6 DISCUSSION

We discuss the implications of the user-defined above-the-neck gestures designed by and for people with motor impairments to interact with mobile devices.

6.1 Key Takeaways

By involving people with motor impairments in the design process and resolving conflicts in the proposed gestures, we uncovered a set of user-defined above-the-neck gestures and how people with motor impairments would want to use these gestures to execute commands on a touchscreen mobile device. All gesture elicitation study participants mentioned they would like to use the gestures to interact with mobile devices in the future. Moreover, participants with motor impairments preferred gestures that were simple, easy to remember, and had high social acceptance. Although they had the freedom to include eyes, mouth, and head into the design of the gestures, gestures involving eyes were still the most diverse and preferred, followed by the gestures combining eyes and head. This finding is consistent with the literature [17, 29] that people like to add head movements to eye-based gestures. Our survey study found that people with and without motor impairments generally agreed on the set of user-defined gestures.

6.2 Design Considerations for User-Defined Gestures

Compared to the eyelid gestures designed by the researchers [10, 11], our user-defined gestures are unique in two aspects. First, our gestures are grounded in the preferences and creativity of people with motor impairments. Second, our gestures are more diverse, which not only include eyelids but also eye motion and other body parts (e.g., head and mouth), and are more expressive and can be used to accomplish more commands. However, one must be wary of the downside of a more diverse set of user-defined gestures.

First, as the number of user-defined gestures increases, the efforts for remembering the mapping between the user-defined gestures and the corresponding commands also increases. Indeed, some participants asked us in an apprehensive tone whether they would have to remember all the gestures they created throughout the study. Thus, it is worth investigating how best to help people with motor impairments make use of these user-defined gestures with the minimum burden of memorization. One possible solution might be to suggest relevant user-defined gestures based on the initial input of the user. For example, if the user starts to close one eye, then the system could recommend a much smaller set of gestures starting with "close one eye."

Second, some participants were concerned that long-term or frequent use of some gestures might develop a bad habit. For example, P15 designed a gesture that required him to tilt his mouth to the left side to use it, and he was worried about creating a bad habit of tilting the mouth. Perhaps when designing user-defined gestures for people with motor impairments, we need to consider not only the gestures' simplicity and social acceptance but also the gestures' long-term health implications.

Third, we derived a standard set of user-defined gestures by resolving conflicts between the gestures proposed by different participants. While the standard set might be the most applicable set for a group of people with motor impairments, the set might not be optimal for a particular user. Users may have different physical conditions and habitual perceptions. For example, if a user could not close her left eye well, then she should be able to skip all the gestures involving closing the left eye and define her alternatives. If the users prefer to use their eyes, they should have the flexibility to use eyes-only gestures instead of head-involved gestures. In addition, as mentioned above, if users are concerned about potential negative health effects of performing the same gesture too often on their face, they could choose to allocate multiple gestures to trigger one command. Thus, it is important to make this standard set of user-defined gestures applicable so that an individual user with motor impairment could customize it. The personalization could be users assigning multiple gestures to one command or assigning the same gesture to different commands.

Lastly, social acceptance was a key factor that people with motor impairments considered when designing the gestures. However, little is known whether people with motor impairments perceive as socially unacceptable are really unacceptable from the public's perspective and vice versa. Furthermore, it also remains unclear what gestures are more socially acceptable. Perhaps gestures that are small in amplitude and consistent with normal daily routine activities might be more socially acceptable. One interesting question would be to understand the relative social acceptability of our user-defined gestures.

7 LIMITATIONS AND FUTURE WORK

Potential Effect of The Presentation Order of Commands. When defining gestures, the participants were given the commands randomly. Thus, they were not able to know in advance the complexity of all commands or whether there were similar or symmetrical commands. Our approach to alleviating this potential presentation order effect, as stated in Section 3.3, was allowing the participants to change the gestures assigned earlier anytime during the study. If they had difficulty keeping track of the assigned gestures, for example, forgetting about what gestures had been already assigned, they could ask the moderator to remind them. Our approach was promising based on the final gesture set shown in Table 3. For example, different commands had been assigned with different gestures, and symmetrical gestures were given to symmetrical commands. Nevertheless, it is interesting to investigate whether participants would adopt different strategies to allocate gestures to commands if they were allowed to know all the commands upfront.

Command Selection. We explored 26 commands commonly used on a touchscreen smartphone. However, these commands are not exhaustive. For example, participants mentioned other commands, such as returning to the main screen, unlocking the phone, and back to the previous page. In addition, our classification of commands was based on the prior work [10, 11, 20], and we divided the 26 commands into three categories based on the task goals. Different classification methods may also affect the participants' choice of gestures. Future work could apply the same principles to define user-defined gestures for additional commands. However, one challenge is to resolve conflicts among the gestures allocated for different commands, which has proved to be increasingly challenging with more commands to cater.

Common vs. Personal User-defined Gestures. Our study aimed to identify a set of common user-defined gestures for the commands often performed on a touchscreen mobile device by a group of people with motor impairments. Thus, we believe that this set of user-defined gestures is a good starting point for people with motor impairments to interact with mobile devices without touch. However, we acknowledge that people with motor impairments have different residual motor abilities and may be able to or prefer to perform different gestures. Thus, it is imperative to investigate how best to allow people with motor impairments to design a *personal* set of user-defined gestures tailed to their specific motor abilities, such as a recent work by Ahmetovic et al. [1].

Differences Between People With and Without Motor Impairments. Our survey study revealed the preferences of people with and without motor impairments were mostly consistent. However, it remains unknown why people without motor impairments preferred the same or different user-defined gestures for the same command or whether they care about social acceptance of these gestures as much as people with motor impairments do.

Potential Effects of Age and Culture. Our participants were primarily young and middle-aged people. It remains an open question of whether age plays a role in user-defined gestures. Future work could replicate the study with older adults with motor impairments and examine whether the user-defined gestures are applicable across different age groups and whether there are specific user-defined gestures that are more preferred by an age group.

Our participants lived in Asia, and they were used to the culture of the East. The creation and preference of user-defined gestures might be affected by culture, and the social acceptance of the gestures was also likely related to the social norms and cultures they lived in. Future work could explore user-defined gestures for people with motor impairments in different cultures and compare the similarities and differences to understand cross-culture and culture-specific user-defined gestures.

8 CONCLUSION

We have adopted a user-centered approach by involving people with motor impairments to design user-defined above-the-neck gestures for them to interact with touchscreen mobile devices without touch. By analyzing the 442 gestures and resolving conflicts, we have arrived at a set of user-defined gestures. The participants were excited about the convenience the gestures could bring to them. They preferred gestures that were simple, easy to remember, and had high social acceptance. Our follow-up survey study results found that the user-defined gestures were well received by both people with and without motor impairments. Finally, we also highlight the design considerations and future work.

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