Understanding Grip Shifts: How Form Factors Impact Hand Movements on Mobile Phones

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ABSTRACT
In this paper we present an investigation into how hand usage is affected by different mobile phone form factors. Our initial (qualitative) study explored how users interact with various mobile phone types (touchscreen, physical keyboard and stylus). The analysis of the videos revealed that each type of mobile phone affords specific handgrips and that the user shifts these grips and consequently the tilt and rotation of the phone depending on the context of interaction. In order to further investigate the tilt and rotation effects we conducted a controlled quantitative study in which we varied the size of the phone and the type of grips (Symmetric bimanual, Asymmetric bimanual with finger, Asymmetric bimanual with thumb and Single handed) to better understand how they affect the tilt and rotation during a dual pointing task. The results showed that the size of the phone does have a consequence and that the distance needed to reach action items affects the phones' tilt and rotation. Additionally, we found that the amount of tilt, rotation and reach required corresponded with the participant's grip preference. We finish the paper by discussing the design lessons for mobile UI and proposing design guidelines and applications for these insights.

Author Keywords
Handgrip; Mobile device; Grasp; Design; Interaction.

ACM Classification Keywords
H.5.2. User Interfaces: Input Devices and Strategies.

INTRODUCTION
We use our hands to interact with the physical world in numerous ways. As Napier [8] points out, our handgrip changes depending on the affordances of the object and the context of the interaction. For example, we use a 'power grip' to initially loosen the top of a jar and then a 'precision grip' to remove the lid. When completing certain tasks it is also common to use both hands. Guiard [1] stated that hands are used together to divide the work; when writing, for example, the non-dominant hand holds the paper while the dominant hand uses the pen to write.

Given this knowledge about the hands' capabilities, it is surprising that so much of the field of mobile interaction focuses on the screen in isolation while ignoring the richness of interaction possibilities that hands offer. The physical form, with its rich physical hand-object interaction potential is almost entirely ignored, so it is therefore somewhat ironic that these devices are termed *handheld*. Researchers have previously explored how to use grasp and orientation information to enrich the interaction, e.g. by helping selection of an action item on the device through pointing [6,7,10] or changing the orientation of the phone to landscape [4]. However, these works only focus on specific applications or hardware implementations. There is a lack of empirical research that investigates the combination of movements and grips that the hand makes when performing common tasks and we are not aware of any work specifically exploring interactions with different form factors, interface types or device size.

Our goal is to systematically explore how mobile form factors affect hand usage. Such exploration is not easy to perform however, due to the high dimensionality of the space: It can be argued that the size, task, interaction style, grip and position of widgets all have effects on hand manipulations. To address this issue we adopted a two-step approach: (1) we performed a qualitative study in which phone size, task and posture are fixed and the interaction style varied (touchscreen, physical keyboard and stylus). The results showed a range of observed grips that differed for each phone type, as well as tilt and rotational movements produced through the hands' manipulation of the phone. We then used these finding to inform the choice of factors to be studied in (2) a quantitative study where we fixed the posture and interaction style and varied the size (iPhone 4,5,6 and 6+), the grip (Single handed, Symmetric bimanual, Asymmetric bimanual with thumb and Asymmetric bimanual with finger) and the position of widgets through a dual pointing task. The results showed

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that the tilt and rotation of the mobile phone were different with each grip type and phone size.

We believe that understanding the changeability of 'hand interaction' and the context within which it is used will enable designers to improve mobile device design. To demonstrate how designers can use our findings, we conclude this paper by proposing three designs. This final exercise is intended to provoke discussion around the current approach to mobile device design.

RELATED WORK

Previous work has leveraged sensory technology to map the placement of the static hand when completing a number of tasks: Firstly, static grips have been used to predict the mode in which the mobile device was being utilised (e.g. camera, phone call or game play) [3]. Secondly, they study the context of screen orientation by defining the grips used when viewing the mobile device in landscape or portrait [4]. Thirdly studies have sought to identify how sensory technology might potentially differentiate between static grips defined by the researchers [9]. Most recently researchers have looked at screen-based sensor technology in order to create an adaptive UI that updates depending where the fingers or thumbs are placed [23].

What these approaches do not do is investigate the hands' fluid transitions or movements, and this is critical because movement in between direct interactions are actually key to the interactions themselves because each movement sets up the conditions for the next interaction.

Gripping

The gripping of mobile phones has also been investigated in a number of ways. Firstly, mathematical modelling of the human hand has been used to look at the reach of the static grip and the thumb [13]. Secondly virtual modelling of the human hand has been exploited to investigate the ergonomics of the hand using 3D rendered objects within the virtual world [27]. Thirdly, comparisons have been made between the use of the static single-handed grip in the dominant and non-dominant hand [25]. Fourthly, a single device was used to examine how the hand grips a button-based mobile phone [26] and lastly, a single device was used to look at how the hand is used when typing on a touchscreen keyboard [28].

Pre-Touch Sensing for Mobile Interaction

Existing research into transitions or movements have focussed on the constraints of using a single-handed grip to interact with the device by tilting it to bring it into range of the thumb [6,7,10]. These works focus on a single device type and single device size. What this research does not consider is a comparison of device types or sizes with different grip types and how this movement is used when the participant completes a task.

Back of device interaction

Research on how a user's fingers interact with the back of the device has been investigated through video analysis, sensors and the transfer of paint from gloves worn by participants [16,17,18]. These works have highlighted how static grips are dependent on application context. It is this back of device surface area that has spurred a number of researchers to investigate how the grasping fingers can be used for secondary interaction by allowing the user to physically tap or gesture on the back of the phone [22,24]. What these approaches do not do is take into account the fluid role the fingers grasping the back of the device play, especially with Single handed, Symmetric bimanual and Asymmetric bimanual with a thumb grips.

Other researches have looked at tablet devices and how UI elements could be adapted to depend on the type of grip used [5]. These works are of less relevance since larger devices are bound to enable different insights and the researchers were focusing on keyboard interaction, rather than the full user journey to task completion.

FIRST CONTROLLED STUDY

The first study was conducted to comprehend how users handle mobile phones of similar size but with different physical interaction methods. We fixed the participants' task, posture and mobile phone size and allowed them to choose their preferred grip when using three different mobile phone types: touchscreen, button-based keyboard and stylus.

Apparatus

The three phones used were of varying vintage. They were selected due to their similarities in size and difference in interaction styles rather than their representation of the current market. The models selected were the iPhone 4 (H:115.2mm, W:58.6mm, D:9.3mm) for 'touchscreen', the Blackberry Bold (H:109mm, W:60mm, D:14.1mm) for 'button-based keyboard' and the Sony Ericsson P1i (H:106mm, W:55mm, D:17mm) for 'stylus' (Figure 1).

Figure 1. The mobile phones used during the sessions (Sony Ericson, Blackberry and iPhone 4)

Task

18 participants were invited to a one-to-one session with a moderator. All participants sat at a table to complete the task. This fixed position enabled us to gather consistent video data of the hands' interaction via three synchronous cameras and focus the studies findings on the phones interaction style and grips selected by the participants.

In order to create an ecological setup, we chose a messaging task. In particular, we asked each participant to follow a scenario that stimulated real life conditions: they were presented with the three mobile phones pre-set to the home screen. Participants were asked to pick up the phone, open the texting application, write a given text, enter a given phone number and then send the text. The pre-defined text message and number were given to them on an A4 printout. The order in which the devices were tested was randomised using the 'Latin Square' method.

Participants were permitted to choose the grips they used and change the grip during the task. Before using each mobile phone, they were asked about their familiarity with the device. Each participant had a short time to get acquainted with the mobile phones before the task started.

Data collection

The videos were analyzed and 'key moments' identified (movement of hands or change of grip) images of which were printed on paper along with participant information. Printouts were used to categorize specific types of grips. We then looked at the movements made during each categorized grip. Movements were visually represented by tracing still images from the video of the hand at the extreme ends of the movement with red marking the starting position and blue marking the end (Figure 3).

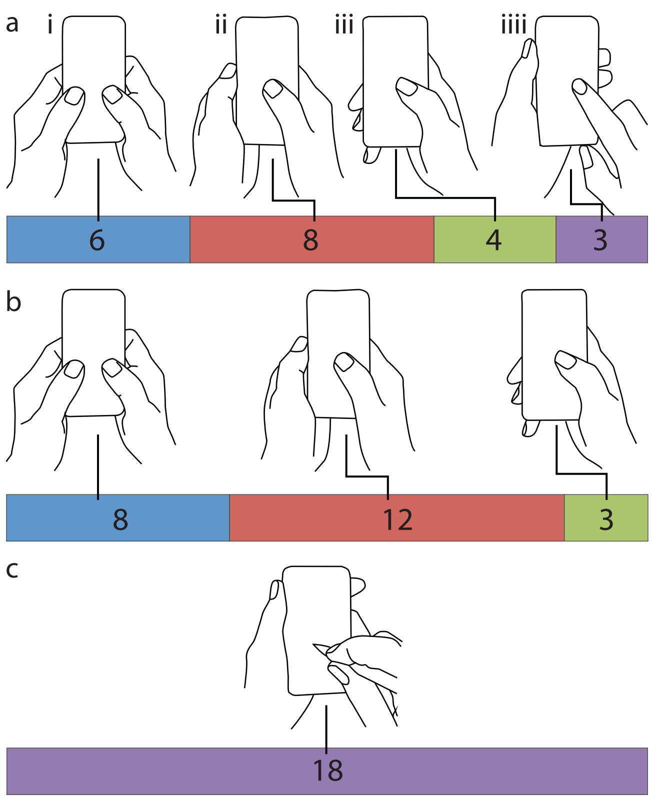

Figure 2. Overall number of participants who used the shown grips with the three mobile phones

Results

The study brought to our attention two areas for consideration. Firstly, when completing the task, the participants used numerous grips and these differed according to the phone in use. For example there were four different touchscreen grips (Figure 2a), three button-based grips (Figure 2b) and one stylus-based grip (Figure 2c). Secondly, the observations highlighted that the participants made slight movements by tilting and rotating the mobile phone in order to reach key interactive areas. Note that our description of the results of this study are condensed here and focuses on the touchscreen device. Additional details for the other devices can be found in [14].

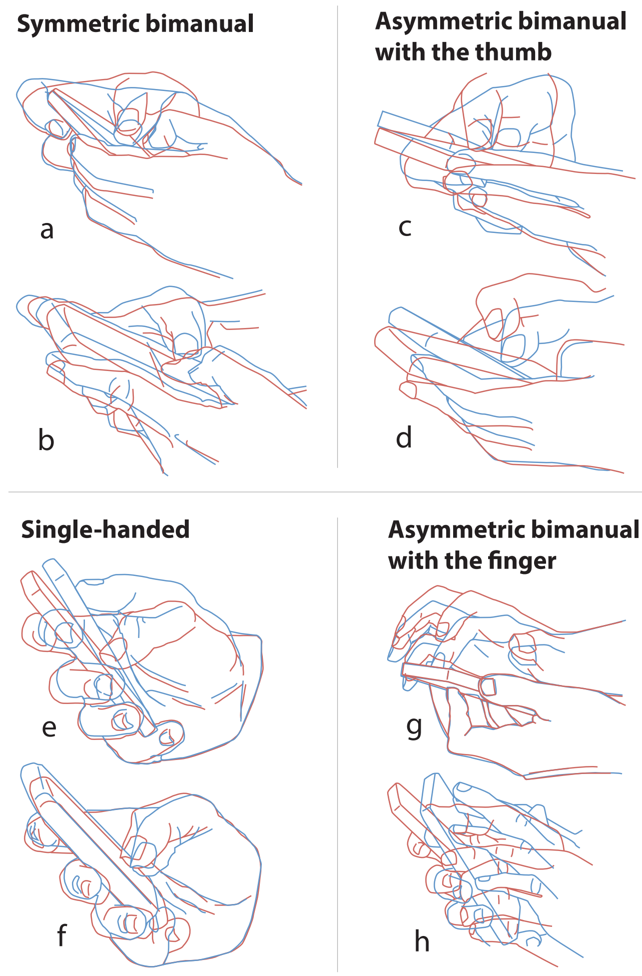

Figure 3: Visualization of the hand movements taken from the video footage (red is starting point and blue the end point

Area 1: Hand Grips

We observed that for the touchscreen device the participants used four specific grips: Symmetric bimanual (Figure 2i); asymmetric bimanual with the thumb (Figure 2ii); single-handed (Figure 2iii) and asymmetric bimanual with the finger (Figure 2iiii). 15 participants used just one grip to complete the task, whereas three participants switched and used two grips. The participants who changed grips did so in response to context: they used one grip to select a menu item, changing to another in order to input data through the device keyboard.

Area 2: Phone movement

17 participants made small movements with the touchscreen phone so that they could reach the key interaction areas during the task.

Symmetric bimanual: Six participants used the symmetric bimanual interaction with the touchscreen phone (Figure 2i). Through observation, we found that the movements for symmetric bimanual grips occurred when participants alternated between thumbs to type on the keyboard (Figure 3a & 3b).

Asymmetric bimanual with the thumb: Eight participants were observed using the asymmetric bimanual with thumb interaction with the touchscreen phone (Figure 2ii). The non-dominant hands were observed supporting the phone either by using the index finger on the side or by cupping the phone with the whole hand (Figure 3c & 3d). In each instance both hands manoeuvred the phone so that the dominant hand's thumb had greater access to the target area. The movements occurred when participants changed approach from typing on the keyboard to selecting the next step or mode. Additionally, movement was observed when the dominant hand's thumb moved around the keyboard.

Single-handed: four participants used only their dominant hand to hold and interact with the touchscreen phone (Figure 2iii). The majority of single-handed movements occurred when a participant attempted to get better access to the lower part of the keyboard by lifting the phone up with the little finger (Figure 3f). Participants also tilted the phone so that their thumb could reach the top of the phone (Figure 3e).

Asymmetric bimanual with the finger: three participants used a single finger to interact with the touchscreen phone. They grasped the phone in the non-dominant hand and used the index finger of their dominant hand on the touchscreen (Figure 2iiii). We observed that two types of movement occurred; firstly the dominant hand's finger moved towards the screen, while the phone, being held in the non-dominant hand, did not move (Figure 3g). Secondly, the non-dominant hand aided interaction by moving the phone towards the dominant hand's index finger (Figure 3h).

Summary

Due to their seated posture all of the participants had their forearms on the table. This placement enabled the use of a rolling motion of the participants' wrists that helped them manoeuvre the phone.

We observed a horizontal side-to-side tilt used with the symmetric bimanual mode (Figure 3b). Participants employing the asymmetric bimanual grip with the thumb also used a side-to-side movement but added a horizontal twisting motion (Figure 3c). Participants using single-handed interaction exploited the same movements but with greater emphasis (Figure 3e). The asymmetric bimanual grip with a finger (Figure 3g & 3h) had similar movements, each employing a twisting motion that maneuvered the phone towards the dominant hand.

SECOND CONTROLLED STUDY

The goal of the second study was to further explore the participant-defined grips and the tilt and rotation of the devices observed in the initial study. In particular we wanted to empirically look at how device size and handgrips affect the phone movement.

We chose to study only the touchscreen interaction method and dropped stylus and keyboard phones for two reasons: (1) because the touchscreen phone was consistently used with all different hand grips in the observational study while the other were not, and (2) in order to reduce the number of independent variables, so allowing a more compelling and balanced experimental design. In order to control the position of the finger movements and analyze how these positions impact the phones' movement, we chose a pointing task (pointing consecutively at two targets on a screen).

Participants

16 right-handed participants (7 males and 9 females) aged between 18yrs to 50yrs were invited to take part in a one-to-one session with a moderator. The participants' hands ranged in size: Length from 205mm to 165mm, Width from 95mm to 78mm, thumb length from 73mm to 55mm and finger length from 91mm to 74mm. As in the first study each participant sat at a table to complete the tasks, so ruling out interference from posture or whole-body movement. This position also enabled us to gather consistent video data of the hands' interaction via two synchronous cameras (Figure 4).

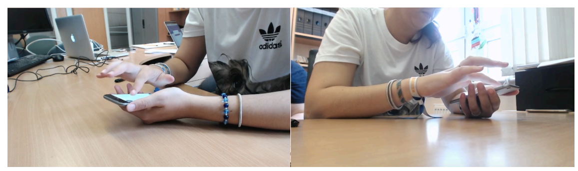

Figure 4. Example of video footage taken.

All participants owned touchscreen phones: six owned iOS devices, one a Windows phone and nine had Android OS devices. Participants had owned their mobile phones from between one month to three years. 12 of the participants had modified their mobile phones by adding an external casing. The participants' mobile phone sizes ranged from W:58.6mm, H:121.55mm, D:6.8mm to W:78.6mm, H:159.3mm, D:11.6. The smallest mobile phones were the Samsung Galaxy mini and Apple iPhone 5s while the largest were the Nexus 6p and Apple iPhone 6+.

Task

Each participant was given the mobile phone running a web application we developed to gather data. The app showed an illustration of the handgrip they had to assume (Figure 5a). When ready each participant clicked on the center of the screen to go to the Start Page (Figure 5b). By pressing the 'Next' button, they triggered the pointing task. Participants were instructed to consecutively select Target 1 and Target 2. Errors triggered a discordant note while successful interactions were rewarded with a more harmonious sound. Participants could take as long as they wished and could take a break between tasks if needed, but had to finish the two pointing tasks appropriately before continuing with the next target task. Each participant was instructed to be as accurate as possible. On successful completion of the task the 'Next' button was displayed again, preparing the user for the next two targets. Once all the target conditions were tested, the screen showed a new grip that the participants had to assume, and the experiment continued as previously described.

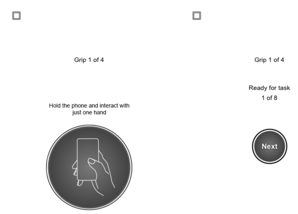

Figure 5. The web interface displays (a) the handgrip that should be used and when clicked displays (b) a 'Next' button that also appears between each task

At the beginning of the experiment, participants were asked to place their hands on an A3 sheet of 1mm graph paper and the hand outlines were traced (Figure 6). Once the tasks were accomplished for a particular mobile phone, participants were asked to complete a questionnaire using a "Likert scale" ranging from 1 to 7. Each grip had three associated questions: 'How comfortable'; 'How secure' and 'How popular' the grip was for the completion of the assigned task.

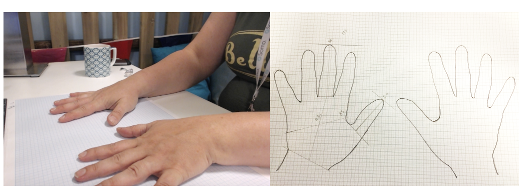

Figure 6. Recording a Participant's hand size

Apparatus

The apparatus included the phones used, the application created and the cameras that recorded the sessions.

Figure 7. The mobile phones used (iPhone 4,5,6 & 6+)

Phones

To maintain consistency with the first study we used a range of device scales, in this case by picking a mobile phone range that already had predefined sizes selected by the manufacturer; Apple. The four mobile phones selected were the iPhone 4 (H:115.2mm, W:58.6mm, D:9.3mm), iPhone 5 (H:123.8mm, W:58.6mm, D:7.6mm), iPhone 6 (H: 138.1mm, W:67mm, D:6.9mm) and iPhone 6+ (H:158.1mm, W:77.8mm, D:7.1mm) (Figure 7).

Application

We implemented a custom-built canvas html responsive web application that tracked the participants' interaction in two ways. (1) By tracking the mobile phones' movements through the inbuilt accelerometer and gyroscope and (2) tracking the participants' physical interaction by recording their button presses in order to make sure they performed the task properly. Through an administration page, the moderator was able to select the mobile phone type and the order the grips were presented to the participants. The size of the targets was 14mm diameter as advised for finger input by Holz and Baudisch [15].

Cameras

We also recorded participants using two Logitech C920 USB HD Pro Webcams connected to a MacBook Pro and viewed through the 'HeadsUp' camera viewing application by Keisi L.L.C [19]. A custom-built web application was shown using the web browser 'Frameless' by Jay Stakelon [21]. To record the MacBook Pros screen and consequently the synchronized cameras, we used the Sliverback 2 screen capture application by Clearleft [20].

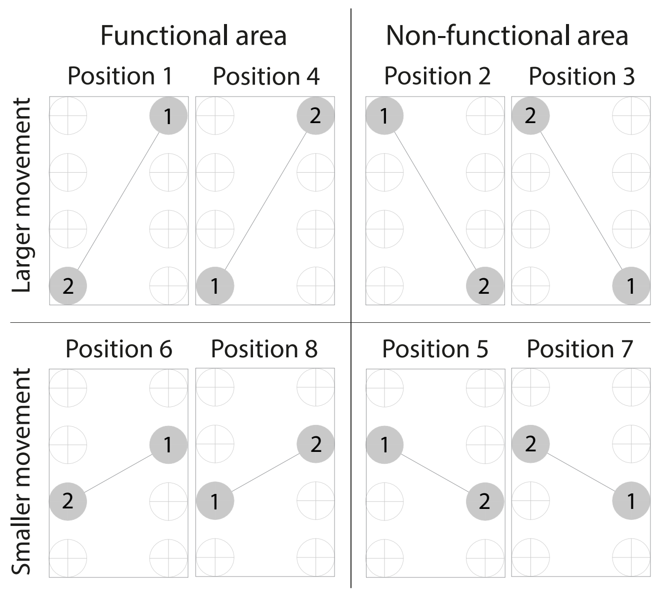

Figure 8. Possible target positions

Experimental design

We conducted a within-subject experiment with three independent variables: Phone Size (four different size detailed in apparatus), Hand Grip (four different types: Symmetric bimanual, Asymmetric bimanual with finger, Asymmetric bimanual with thumb and single handed), and Target Position (eight different combinations of Target Positions shown in Figure 8). Grips and Size were randomized using the "Latin square" method. The Target Positions were randomized within each block. In total we had four Phone Sizes x four Grips x eight Target Positions

= 128 double tapping task = 8 minutes 51 seconds per participants on average.

Hypotheses

Following the initial observations from the first study we draw a list of hypotheses described below.

H1: The larger the phone, the larger the phone movement. A larger phone might be more difficult for the user to reach target areas with the hand and thus the users will have to tilt the phone to stretch across the screen to the targets, especially those placed at the extremities of the screen.

H2: The amount of movement of the phone will differ according to handgrip. Single-handed (S) will have most movement, followed by Asymmetric with a thumb (AT), Symmetric bimanual (B) and Asymmetric with a finger (AF). We postulated that the more the hand needs to physically stretch and exert, the more the phone will need to be moved and tilted.

H3: The amount of phone movement will differ according to Target Position (more movements for targets further away). Target 1's starting location and the direction users need to shift their hand to reach Target 2 will affects the degree of phone movement. E.g. Target Positions 2,3,5 and 7 require the hand to reach away from the dominant hand's location, whereas Target Positions 1,4,6 and 8 require less reach by the participant's dominant hand.

H4: The amount of directional movement will change with grip and Target Position. B will have more side-to-side Gamma (y-axis) movements and the movement will be opposite to that of other grips. We should observe greater Beta (x-axis) movement differences between S and AT (i.e. movement needed to bring the phone to the thumb, the converse of AF where the finger will move to the phone).

H5: The amount of directional movement will change with phone size and Target Position. We expect to see opposite movements depending on the orientation of the targets. These movements should increase with phone size.

H6: Phones size and grips that require the participant to make smaller phone movements in order to complete the task will be subjectively preferred and found more comfortable and secure. We assume that configurations implying fewer movements will mean less effort for the users and thus that they will prefer these configurations.

Results and discussion

A Shapiro Wilk test confirmed that the assumption of normality has been met for our data ($p<0.001$). We provide an analysis of the overall movement of the phone below before discussing details about directional movements. The section ends with some analysis of the post questionnaire results. First, however we examine the overall error rate.

Error checks

Our goal was to understand phone movement when selecting the targets rather than measure pointing precision (which is why the tapping task had to be successfully completed before the trial could continue). Nevertheless, it was important to check that participants finished the task without complications, which is why we first looked at errors.

Errors that occurred as participants completed the task were captured in two ways: (1) through manual analysis of the video record to identify when more than one tap had occurred, and (2) through inbuilt analytics that registered when identified taps missed the target area. We defined errors as when a participant required more than one attempt to select a target, either because a target was missed or because the software did not register the interaction. Dropping the phone was also logged as an error.

The analytic measurement showed that the error rate was particularly elevated for two participants especially for the single-handed grip of the iPhone 6 and also larger iPhone 6+ where it became even more pronounced. This corroborated our qualitative observer judgments of the video. These participants also rotated the phone to such a degree that the web app triggered the landscape-viewing mode. These data being clear outliers we decided to exclude them from the phone movement analysis.

Overall movements

We performed an Analysis of Covariance (ANCOVA) on the sum of the absolute values of the accelerometer movements on each axis. ANCOVA is an extension of the analysis of variance (ANOVA) that includes additional continuous variables (covariates) that may have an influence on the dependent variables. For example the size of participants' hands is an important factor that can affect the results.

Because we took four different measures of the hand (Palm width, Palm length, Thumb length and middle finger length) we first performed a Principal Component Analysis in order to reduce the number of dimensions (and consequently the number of factors considered through the ANCOVA). This type of analysis produces a general score (or a component), in our case the *hand size score*, which is arguably a better indicator of general hand size than any of the four measures taken individually. We found that the variances were not significantly different from each other, thus showing that the assumption of homogeneity of covariance holds. We then proceeded to do the ANCOVA.

We found a main effect for phone Size ($F_{3,1791}$=49.135, $p<0.05$), Grip ($F_{3,1791}$=275.165, $p<0.05$), and Target Position ($F_{7,1791}$=109.371, $p<0.05$). We also found an effect for interaction Size x Grip ($F_{9,1791}$=7.159, $p<0.05$), Size x Target ($F_{21,1791}$=2.237, $p<0.05$), and Grip x Position ($F_{21,1791}$=14.567, $p<0.05$). Finally we performed Post-Hoc comparisons using Least Significant Difference (LSD). Figure 10 show the estimated means, i.e. the hypothetical means unbiased by the *hand size scores* after correction by the ANCOVA.

We found that both the grip and the phone size had a strong effect on phone movements. In a significant manner, the single grip (S) produced the most movements, followed by Asymmetric with thumb (AT), Bimanual (B) and Asymmetric with finger (AF). This validates Hypothesis H2 as we successfully predicted the order of the phones' movement based on data from the initial study.

We found significant differences linked to device size. The two smallest phones provoked less movements compared to the two largest ones, although there was no significant difference between the two smallest and two largest respectively. This validates Hypothesis H1, which predicted that larger phones would require larger phone movements.

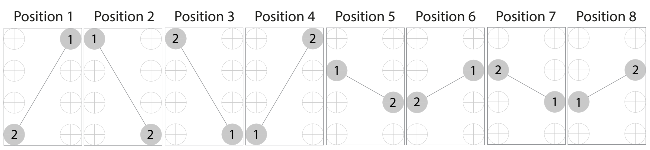

Figure 9. Position locations

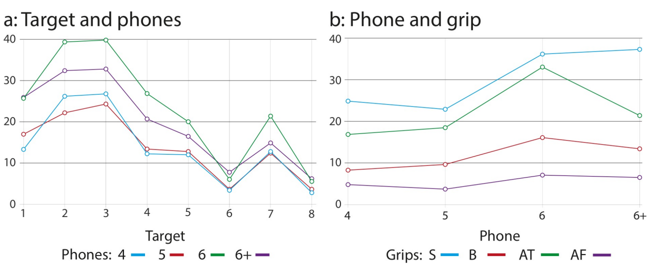

Figure 10. Estimated level of phone movement for the interaction between our different factors

We found that the Functional Area Smaller Movement Positions 6&8 produced fewer movements, followed by the Non-functional area Smaller Movement Positions 5&7, then Functional Area Larger Movement Positions 1&4 and finally the Non-functional Area Larger Movement Positions 2&3 (Figure 10). These results are all significant except for Positions 5&7 and 4. Positions 6&8 (centre of the screen) may be the more stable because they require smaller amplitude of movement from the finger and are also within the 'functional area of the thumb' as described by Bergstrom-Lehtovirta *et al* [13]. Positions 5&7 also require small movements but are not in the functional area of the thumb, which might explain why they require more movement than 6&8. Positions 1&4 require larger movement and are again in the functional area of the thumb while Positions 2&3 are not. A similar trend was found when phone size was examined individually. Thus we found that hypotheses H3 and H4 were validated. Firstly the data show that the amount of movement of the phone will differ depending on the distance between the target positions, and secondly they demonstrate that the location and consequently the direction the hand needs to shift in order to tap, has an effect on the phones movement. Having validated the hypotheses related to the general amount of movement we refined our analysis to consider the direction of the movements in allowing us to test the next hypothesis.

Directional movements

In preparing data for the ANCOVA in this next phase we followed an identical process to that used to assess overall movements. We focused this time on the movements around each axis of the mobile phone: Alpha (z-axis), Beta (x-axis) and Gamma (y-axis) (Figure 10). For Alpha (rotation around Z) we found a main effect for Target Position ($F_{7,1791}$=12.475, $p<0.05$). We also found an effect for interaction Size x Position ($F_{21,1791}$=2.383, $p<0.05$), and Grip x Position ($F_{21,1791}$=9.976, $p<0.05$). For Beta (rotation around X) we found a main effect for Target Position ($F_{7,1791}$=216.906, $p<0.05$). We also found an effect for interaction Size x Position ($F_{21,1791}$=5.078, $p<0.05$) and Grip x Position ($F_{21,1791}$=21.697, $p<0.05$). For Gamma we found a main effect for Target Position ($F_{7,1791}$=213.614, $p<0.05$). We also found an effect for interaction Size x Position ($F_{21,1791}$=5.351, $p<0.05$), and Grip x Position ($F_{21,1791}$=67.990, $p<0.05$). as before we used Least Significant Difference (LSD) for performing Post-Hoc comparisons.

Effect of phone size and Target Positions: The size of mobile phone had an effect on all type of rotational movement. The Alpha movement was affected least while the Gamma movement was affected the most. Figure 11a clearly illustrates the effect that the phone size and target position have with the alpha (z-axis) movement; this movement increasing with the phone size, i.e. the movement is significantly different between target positions 1 and 4. This corresponds to the longest amplitude of movement, with all phone sizes excluding the smallest (iPhone 4). This partially validates Hypothesis H5, which predicted that phone size would change rotational movements around the Alpha (z-axis). We think this is due to the fact that participants tended to rotate the phones in their hand, shifting the grip in order to reach the target. This happened less with smaller phones because a change of grip was enough to allow the completion of the task without the need to rotate the phone.

The trend is very similar along the Beta and Gamma axes of all four phones. There are, however, some significant differences between specific Target Positions. For example, we found that the iPhone 6 had a larger Beta movement with Target Positions 1,2,3 and 4 (the Target Positions with the greatest distance). We also found significant differences for Gamma axis of the iPhone 6 and Target Positions 1,2,3,4 and 7, as well as for the iPhone 5 and Target Position 2.

We expected the iPhone 6 being the second largest phone, to produce significantly greater movement than the iPhone 4 and 5. We also expected this larger movement to be activated by the target positions 1,2,3 and 4 as they had the greatest distance between the targets and by target position 7 which, although had a smaller distance between the targets, also went against the 'functional area of the thumb' and so required participants to reach across the phone. We believe that the iPhone 6+ did not produce the larger movement because the size of the phone required the participants to change the grip shift methods, however a more in-depth analysis is needed to understand this fully.

Effect of grip and Target Positions. As shown in Figure 11, the directional movements differed substantially depending on the Target Position and Grip, thus corroborating our Hypothesis H5. We noticed that the level of movement in the Alpha, Beta and Gamma axes increased with the Gamma increase being the greatest. The exception here is AF that appeared to show only a marginal increase in Gamma rotation. Without going into too much detail about each individual Target Position comparison we can state that there were few significant differences for between Target Positions involving small amounts of movement (5,6,7 and 8). Except for target 5 and 7 with the Gamma axis and Beta axis values of grips S and AT which were larger.

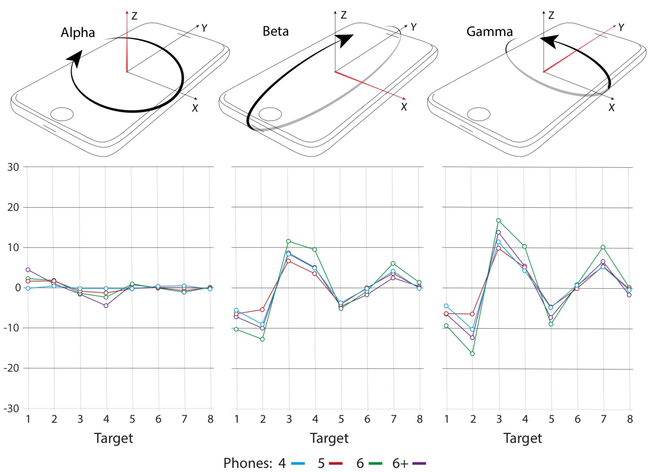

Figure 11. Estimated extent of phone movement in the Alpha (z-axis), Beta (x-axis) and Gamma (y-axis) axes for interaction between phone sizes

Figure 12. Estimated extent of phone movement in the Alpha (z-axis), Beta (x-axis), and Gamma (y-axis) axes for interaction

We found much more significant differences for the Target Positions involving larger movements however (1,2,3 and 4). In particular, the Alpha rotations were comparatively high for AT and very low for S. We believe that this is due to the non-dominant hand acting in support of the dominant hand by maneuvering the phone closer to the thumb's position. Interestingly the direction of rotation also appears

A: Single-handed									
Targets		1	2	3	4	5	6	7	8
iPhone 4	X	9.7	15.1	15.1	9.5	6.6	1.7	8.9	1.5
	Y	6.2	23.0	27.1	7.6	12.1	3.4	12.1	3.4
	Z	4.7	7.7	6.2	3.5	4.7	1.6	5.6	1.6
iPhone 5	X	11.5	14.1	12.9	8.1	7.6	1.5	5.9	1.7
	Y	9.9	15.5	22.4	8.6	11.1	2.4	13.1	2.6
	Z	4.7	9.4	4.9	4.3	3.8	1.6	3.3	1.9
iPhone 6	X	19.4	22.7	18.2	18.6	10.1	3.1	10.0	2.6
	Y	10.7	32.8	36.9	12.4	17.4	4.9	23.1	4.0
	Z	5.3	6.4	5.7	7.1	5.2	2.6	8.5	1.4
iPhone 6+	X	17.7	18.0	17.0	18.0	6.6	5.7	5.7	4.0
	Y	13.9	30.6	35.8	14.7	16.9	8.2	17.4	6.9
	Z	12.5	9.5	8.4	11.9	4.8	4.7	3.9	3.4
B: Symmetric Bimanual									
Targets		1	2	3	4	5	6	7	8
iPhone 4	X	6.0	4.5	4.1	5.2	1.8	1.3	1.4	0.8
	Y	6.9	5.6	4.9	5.2	2.1	1.4	1.4	1.1
	Z	2.3	1.6	4.1	1.8	0.9	0.6	0.6	0.4
iPhone 5	X	6.7	3.2	4.9	3.6	2.0	1.4	1.2	2.2
	Y	8.5	6.2	4.5	5.6	2.3	2.4	2.6	1.9
	Z	2.9	3.9	3.6	3.0	1.1	0.9	1.6	0.7
iPhone 6	X	11.6	7.1	6.8	11.0	2.2	2.1	2.1	3.3
	Y	12.7	8.4	9.6	14.3	3.4	3.0	2.6	4.1
	Z	3.1	4.9	6.4	4.9	1.6	1.1	1.6	0.6
iPhone 6+	X	9.8	7.8	6.4	5.1	3.4	2.7	2.1	2.4
	Y	11.1	7.4	6.9	7.7	2.4	3.9	2.9	2.2
	Z	6.6	3.6	3.5	4.4	2.0	0.8	1.1	0.9
C: Asymmetric with Thumb									
Targets		1	2	3	4	5	6	7	8
iPhone 4	X	5.1	12.8	12.0	5.5	5.8	1.1	6.0	0.7
	Y	5.6	18.3	18.0	6.1	7.0	1.4	8.9	0.9
	Z	2.6	4.9	4.7	2.4	2.1	0.6	2.1	0.2
iPhone 5	X	7.6	10.9	13.3	6.4	7.3	1.4	7.3	0.6
	Y	9.2	15.3	20.2	8.1	9.1	1.1	9.4	0.9
	Z	3.9	3.4	4.8	3.0	2.2	0.7	1.4	0.4
iPhone 6	X	10.2	16.7	17.4	10.9	9.7	2.1	10.9	1.8
	Y	14.1	32.9	34.1	13.4	18.4	2.8	17.4	2.4
	Z	8.3	10.9	10.1	9.1	4.8	1.2	3.9	0.7
iPhone 6+	X	9.1	12.9	10.7	5.4	7.7	1.7	8.6	1.3
	Y	9.9	19.6	19.8	5.4	10.6	1.7	12.4	2.1
	Z	7.9	6.7	5.6	4.9	2.9	0.8	2.6	0.6
D: Asymmetric with Finger									
Targets		1	2	3	4	5	6	7	8
iPhone 4	X	1.6	3.7	3.0	0.9	1.5	0.2	1.1	0.1
	Y	1.2	4.2	4.8	0.7	1.9	0.2	1.7	0.4
	Z	1.3	3.3	3.0	0.6	1.4	0.1	1.2	0.2
iPhone 5	X	0.9	2.6	2.1	1.1	1.8	0.2	1.2	0.6
	Y	1.1	2.5	2.4	1.1	1.8	0.5	1.6	0.5
	Z	0.9	1.8	1.2	0.7	1.1	0.5	0.9	0.5
iPhone 6	X	2.5	4.6	4.1	1.9	2.0	0.4	1.6	0.3
	Y	2.5	5.7	5.6	1.6	2.9	0.6	2.0	0.6
	Z	2.2	4.3	4.2	2.3	2.4	0.1	1.8	0.3
iPhone 6+	X	2.1	4.0	4.1	1.6	2.7	0.3	0.7	0.3
	Y	1.5	5.4	5.7	1.5	3.5	0.3	1.1	0.3
	Z	1.4	4.1	5.0	2.0	2.3	0.3	1.2	0.4

Figure 13. Mean angle data for all targets and grips.

to change depending on the grip, with AF and AT having rotations opposite to B for Target Positions 2 and 3. We believe that this due to the usage of both thumbs and the direction of the movement between the targets.

For the Beta axis rotations, the largest movements were attributed to the S and AT and were significantly higher than those of B and AF, while the direction of movement was similar for all targets. This suggested that participants used the same movement each time to acquire the target i.e. rocking the phone toward them. For the Gamma rotation, there was again a significant different between S and AT vs. B and AF. Figure 12 also illustrates the difference between B and AF, where one can see an opposite movement direction. We believe that this is again due to the B grip where both thumbs are employed to interact with the phone. Users were found to have used a rocking motion along the Gamma axis - i.e. instead of bringing the phone to the finger or thumb, they rocked the phone in opposite direction to reach the target (see Figure 3b).

We observed a strong difference for the combined Gamma and Beta values between conditions where the thumb was used to point (S and AT) and the condition where the index finger was used (AF). The amplitude of movements is significantly stronger for S and AT which could simply be due by the fact that the AF grip allows the user to move their hand and arm more freely and thus bring the finger to the correct position, which necessitates less phone movement (as observed in the initial study). Conversely, S and AT grips constrict the hand more, forcing participants to move the phone substantially further to bring it into contact with the thumb.

Post questionnaire

Using a similar analysis to that described above, we found a main effect for Q1 (Secure) on Phone Size ($F_{3,1791}$=16.536, $p<0.05$) and Grip ($F_{3,1791}$=192.056, $p<0.05$) and Grip x Size ($F_{9,1791}$=30.728, $p<0.05$); Q2 (comfort) on Phone Size ($F_{3,1791}$=13.101, $p<0.05$) and Grip ($F_{3,1791}$=81.297, $p<0.05$) and Grip x Size ($F_{9,1791}$=32.606, $p<0.05$); Q3 (popularity) on Phone Size ($F_{3,1791}$=5.960, $p<0.05$) and Grip ($F_{3,1791}$=62.346, $p<0.05$) and grip x size ($F_{9,1791}$=24.996, $p<0.05$).

Security: The S Grip was significantly rated less secure for iPhone 5, 6 and 6+, however there were no other significant differences. In fact, if we look at Figure 14 we can see that the scores are very similar across a range of grip types and phone sizes, proving that participants felt secure when employing a two-handed grip.

Comfort. The S and AF grips were rated more comfortable than B and AT for the iPhone 4 and 5. However, this trend inverts for S, which is rated the worst for the iPhone 6+. AF remains consistent and is the preferred grip for the iPhone 6 and 6+. For iPhone 6+ the grips B and AT are in second place. The questionnaire data for the S grip corresponds with participants' comments during the task that the smaller iPhone 4 and 5 allowed them to grasp the phone and reach the target areas without much effort. However, as the phone size increased participants found great difficulty in completing the dual role of holding the phone and reaching the target areas. This resulted in larger shifts of grip with one participant complaining of hand strain.

Preference of grip: the trends here are similar to those of the *Comfort* question. In fact, the same significant results were found as described above. As Napier [8] states, the selection of the grip depends on the task required and these results are focused purely on the pointing task. The AF grip is ranked best for three phones (iPhone 5,6 and 6+) and second best for the iPhone 4. The AF grip is also the grip which provokes the least amount of movement (Figure 11) which partially validates our Hypothesis H6.

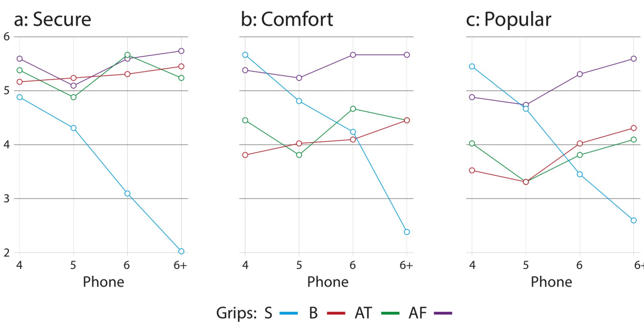

Figure 14. Questionnaire Results: a) Security of the grip b) Comfort of the grip and c) Popularity of the grip for this task

Summary of results

In this second study we looked at how the size of the mobile phone and the grip used affected how the phone was maneuvered. We validated all our hypotheses except for H1 and H6. H1 was partially validated: we found that the two smaller phones had significantly less movements than the two larger ones. H6 was also partially validated: AF is the grip with the least movement and this is preferred for three of the four phones with S being the preferred grip for the remaining phone.

DISCUSSION AND DESIGN GUIDELINES

Both our studies demonstrated that the hand adapts fluidly to device type and context of use, dealing with interactions such as menu selection or keyboard typing through a combination of grips and movements. Can designers use this knowledge to create more compelling interactive experiences? In the last part of this paper we attempt to answer this question through three concepts that exploit insights gained from the above study to propose appropriate design responses focused on a touchscreen-based solution.

Conceptual design

Current touchscreen mobile phone operating systems such as Apple's iOS are designed around a series of UI components [2]. Using these components as a foundation, we generated a number of concepts around an adaptive UI method where UI changes are triggered by a combination of the task and its known tilt and rotational movement associations.

Adaptive keyboard

During the first qualitative study participants were found to tilt the device from side-to-side along the Gamma axis to gain better access to the keyboard target areas (Figure 3b). Building on our hypothesis H3, we discovered that this tilt movement also occurred during the second quantitative study for Target Positions 5,6,7 and 8. Using the data shown in Figures 11 and 13 we see greater movement along the Gamma axis (in other words, a side-to-side motion).

The adaptive keyboard concept in Figure 15 uses this side-to-side motion to shift the keyboard letters into more reachable position. The concept has some similarity with the iGrasp technique [5], but while iGrasp triggers the keyboard according to grip, in this case the adaptive keyboard would be activated if a side-to-side tilt along the Gamma axis were initiated. The keyboard 'slides' as the phone tilts, placing the required letters in an easier-to-reach position for the thumb.

Figure 15: The adaptive keyboard concept

Adaptive scrolling

In the first qualitative study we found that participants tilted the mobile phone along the vertical axis to enable the selection of navigation options from the top bar (Figure 3d and 3e). In the second study participants made similar vertical tilts for Target Positions 1, 2, 3 and 4 along the Beta and Gamma axes, thus building on our Hypotheses H1, H3 and H5.

Figure 16: The adaptive scrolling concept

The concept adaptive scrolling involves activating a feature when two conditions are met: a navigation bar is on the screen and a tilt along the Beta axis is detected. Adaptive scrolling is then triggered, lowering the navigation bar items to place them within reach of the thumb (Figure 16).

Adaptive homepage

In our first qualitative study we found that when participants using the single-handed and asymmetric bimanual with a thumb grips reached for the top corner of the screen opposite the dominant hand's thumb, the phone twisted along the Beta and Gamma axes (Figure 3c and 3e). This area appeared to be difficult to reach and provoked the greatest tilt and rotation of the device. In testing of Hypotheses H1, H3 and H5, the second quantitative study also showed that participants, made similar twists along the Beta and Gamma axes for Target Positions 1, 2, 3 and 4 (see Figures 11 and 13).

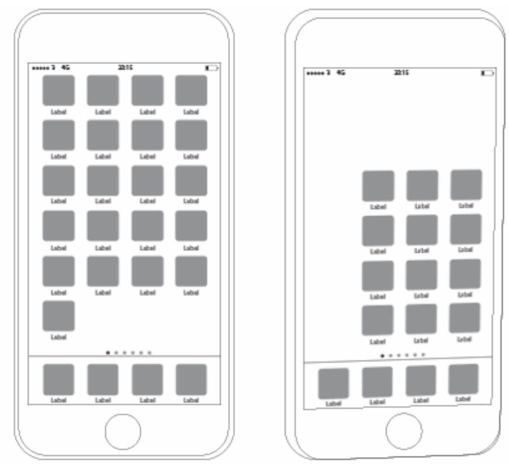

Figure 17: The adaptive homepage concept

The adaptive homepage concept has some similarities with "tilt slide" [10]. In this concept homepage icons shift closer to the dominant hand when tilt is sensed along both the Beta and Gamma axes (Figure 17). This reduces the amount of reach a participant needs to use in order to interact with the phone.

CONCLUSION AND FUTURE WORK

In this paper we used two controlled studies to investigate how the hand grasps and manipulates different handheld device form factors. We used the insights gathered from the studies to propose mobile UI concepts, which demonstrate how designers can benefit from understanding how the hand and phone movements change according to phone size and grip type. To progress this research, we intend to investigate how participants' location and posture may further alter the phone and grip movements. For instance, we think that the posture of the user (lying, sitting or standing) and whether or not their hand or arm is supported might change the results.

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