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How Wide Is Enough? Effects of Screen Height, Task Type, and Hand Length on Rollable Display Requirements

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ABSTRACT Although rollable displays must be unrolled for on-screen interaction, it is unknown whether screen height, task type, and hand length affect rollable display requirements. This study examined the effects of screen height, task type, and hand length on the rollable display requirements. A total of 30 young individuals (22.9 ± 2.3 years; 10 in each hand-length group) performed three tasks (web searching, video viewing, and e-mail composition) using three prototypes with different screen heights (H) of 50, 120, and 190 mm. Dependent variables were preferred screen width, preferred screen width-to-height aspect ratio, user satisfaction, gripping comfort, device portability, design attractiveness, and gripping method. As screen height increased, the preferred screen width increased, but the preferred screen aspect ratio decreased. The 95th-percentile screen width (aspect ratio) of 100 mm (2:1) was required for 50H versus 204 mm (1.7:1) for 120H and 304 mm (1.6:1) for 190H. The highest 95th-percentile screen aspect ratio of 1.9:1 was required for video viewing. The long-hand-length group preferred significantly wider screens for 190H only. Bilateral grasping was predominantly used for 50H and 120H, whereas non-grasping was for 190H due to limited thumb reach and insufficient screen reaction force. Considering user satisfaction, device portability, and design attractiveness, 120H was recommended, and a screen aspect ratio of 2:1 appeared sufficient for the performance of three mobile tasks on a 120H rollable screen.

INDEX TERMS Ergonomics, human computer interaction, human factors, product design.

I. INTRODUCTION

Mobile devices with a fixed-size non-flexible display cannot effectively accommodate diverse user needs and tasks, as evidenced by the possession and alternative use of multiple smart devices (e.g., small- and large-screen devices for texting and video viewing, respectively; [1], [2]) as well as the introduction of foldable display applications (e.g., foldable smartphones; [3]). Indeed, in a formative usability study of foldable-display device concepts [4], a small screen (120 mm height (H) × 60 mm width (W); 120H × 60W) was suitable for making voice calls only and a medium screen (120H × 128W) for gaming and web searching. As opposed to non-flexible displays, flexible displays (e.g., foldable, rollable) enable a single device to accommodate two important, yet mutually conflicting user needs of a compact device size for portability and a large screen for visual effects [4]. In this regard, rollable displays are apparently more effective to varying user needs than foldable displays. Specifically, a rollable display device can increase its display size continuously up to the completely unrolled display size, whereas a typical foldable display device is designed to be folded in half or a third, and hence provides only several display sizes [4].

The effects of wide screen are inconsistent. Wide screens require less scrolling [5], [6], and improve legibility [5], [7], immersion [8], and proofreading performance [9]. Furthermore, wide screens reduce wrist extension during mobile device gripping, and large on-screen buttons can reduce

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input errors [10]–[12]. Conversely, excessively long text lines can reduce legibility [13]. Moreover, wide screens adversely affect gripping comfort, one-handed screen operation [14], and portability [13], [15]. Large, heavy devices likely increase muscle fatigue and restrict gripping methods (e.g., by requiring higher grip strength or external (lap or table) support). Therefore, unnecessarily wide screens should not be utilized in portable display devices.

Most people, however, prefer wider screens over narrower screens, with visual effects prioritized over gripping comfort [14]. Smartphone screen height-to-width aspect ratios (and screen sizes) have continuously increased. Since the first debut of the iPhone$^{\mathrm{TM}}$ (Apple, USA) featuring a display of a 3:2 aspect ratio, displays of a 16:9 aspect ratio have been featured by most subsequent smartphone models, and displays of an 18:9 (2:1) or above aspect ratio have been implemented for some recent models. Although the screen size adjustability of rollable-display devices is expected to improve user experience (UX) by providing both better portability and visual effects, the rollable screen size requirements remain unknown.

Mobile device forms affect gripping comfort, design attractiveness, and gripping methods. In a study [16] on index-finger input on the rear surface of smartphones, a 60-mm-wide model yielded higher one-handed gripping comfort than a 90-mm-wide model. In a study [17], the curved display excessively reduced smartphone side thickness, resulting poor gripping comfort. Indeed, smartphone dimensions of 140 mm (H) × 65 mm (or 70 mm) (W) × 8 mm thickness (T) × 2.5 mm edge roundness (R) and 122 g mass are recommended for high one-handed gripping comfort and design attractiveness [15]. Similarly, in a rollable-display device study [18], gripping comfort increased with increasing device thickness from 2T (2-mm thickness) to 10T (6T being comparable to 10T). Regarding gripping methods, a study [15] argued that compared with the conventional taxonomy of power and precision grips based on the palm involvement in grasping [19], the dynamic grip [20] describes the gripping methods for non-flexible smartphones more effectively, i.e., secure dynamic grip for making calls versus less secure dynamic grip for the other tasks. To access a rollable screen, the screen should be unrolled by lateral pulling. Device gripping methods for this motion include a lateral pinch [18], a type of power grip (involving two virtual fingers of the thumb and other fingers; [19]), a pulp or tip pinch (involving the thumb and index-finger pulps; [18], [21]), and a palmar pinch (involving the thumb, index-finger, and middle-finger pulps; [21]). Similarly, diverse gripping methods would be used for touch interaction on a rollable screen: one or two hands are used to grip the device (or no hands when the device is laid down) while one or two thumbs (and/or fingers) are involved in touch interaction, for which less secure dynamic grips (or non-grasping) would be adopted, although actual gripping methods for rollable display devices remain unknown. It is thus necessary to examine the effects of rollable device forms (including screen size) on gripping comfort, design attractiveness, and gripping methods, as in the studies of non-flexible smartphones [10], [15], [18], [22]–[26] and foldable-display devices [4].

The screen size and aspect ratio requirements for mobile devices appear to be task dependent. Frequently performed smartphone tasks include instant messaging, making voice calls, web searching, video viewing, and gaming [27]–[32], whereas e-mailing is less frequent. Frequently performed tablet PC tasks include information-related activities (e.g., web searching), content consumption (e.g., video viewing and reading), social activities (e.g., e-mailing and blogging), gaming, and instant messaging, with the exception of making voice calls [33], [34]. In a study that determined the preferred screen sizes for five mobile tasks (instant messaging, making voice calls, texting, web searching, and gaming) using three foldable-display device prototypes with an identical screen height (120H) but three different screen widths (60W, 128W, and 196W for non-foldable, bi-fold screen, and tri-fold screens, respectively; [4]), 60W was preferred for making voice calls, whereas 128W was preferred for the remaining tasks, which involved frequent screen touch interactions and information acquisition from the screen. Typing accuracy could decrease if the screen, on-screen keys, or inter-key spacing is too narrow [17], whereas one- or two-thumb interaction could be uncomfortable if any of these is too wide [14], [35]. Because the size of a rollable screen is changed continuously (versus discrete changes in the size of a foldable screen), the preferred rollable screen sizes potentially differ from the above results, and thus necessitating determination of rollable-screen size requirements for diverse tasks.

Hand characteristics should be considered when designing mobile devices. The glabrous hand skin pressure sensitivity varies, especially in the proximo-distal direction [36], and gripping postures for identical objects can differ with hand size [37]. In a study of index-finger input on the smartphone rear surface [16], the small-hand group reported the highest mean hand discomfort and percentage of maximum voluntary contraction related to index finger flexion compared to the other two groups. In a study [38], comfortable handle diameters increased with hand length (37.3-39.6, 39.6-42.0, and 42.0-44.3 mm for the small-, medium-, and large-hand groups, respectively). Similarly, for the gaming task, the long-hand-length group preferred the widest screen among three screens of 120H × 60W, 120H × 128W, and 120H × 196W [4]. Although hand length did not significantly affect gripping comfort for rollable-screen prototypes in a study [18], this study focused only on the gripping comfort for completely unrolling a rollable-display prototype with a fixed screen height, and did not consider screen-touch interaction tasks. Thus, it remains necessary to comprehensively examine the effects of screen height, screen-touch-related tasks, and hand length on the gripping comfort, rollable screen size requirements, and other UX-related measures.

The objective of this study was to examine the effects of rollable-screen height, task type, and hand length on the preferred screen width, preferred screen aspect ratio, user satisfaction, gripping comfort, device portability, design attractiveness, and gripping methods, ultimately to determine rollable screen size requirements. Specific hypotheses were that rollable-screen height, task type, and hand length independently or interactively affect the preferred screen width, preferred screen aspect ratio, user satisfaction, gripping comfort, device portability, design attractiveness, and gripping methods.

II. METHODS

A. PARTICIPANTS

A total of 30 right-handed individuals (16 men and 14 women) with a mean (SD) age of 22.9 (±2.3) years participated in this study. No participant reported any musculoskeletal diseases of the upper limbs. Additional efforts were made to recruit a group of individuals with a wide hand-length range. The study protocol was approved by a local institutional review board. All of the participants provided written informed consent and were compensated for their time.

B. EXPERIMENTAL SETTING AND DESIGN

The experimental environment was a combination of those used in the previous studies to examine smartphone [16] and tablet PC use [39]; Fig. 1). A Kinect for Windows SDK 2.0 (Microsoft Corp., USA) and beam projector (EB-4950WU, Epson Inc., Japan) were installed approximately 1 m above the desk (Fig. 1). Four reflective markers (PN03458 Scotchlite^{TM} silver reflective tape, 3M, USA) were attached to the side bezels of each rollable-display prototype to track the screen size and tilt angle in real time (Fig. 2). To provide a real-time adjusted image on the prototype screen, custom software was developed using the Kinect and OpenCV for Unity (Enox Software Corp., Japan). A digital camcorder was installed above the participant. The Wizard of Oz method [40] was utilized to simulate touch interactions on the rollable screen. An experimenter who observed the screen inputs made by participants provided corresponding screen outputs.

Each prototype comprised acrylonitrile butadiene styrene plastic panels, two rollers, a roll of paper (to present screen images), and two springs (to retract the paper screen). To ensure high one-handed gripping comfort and design attractiveness [15], 140H × 65W × 8T × 2.5R was used as a reference device size for the retracted rollable-display prototypes. The three prototypes had different screen (device) heights: 50H (70H), 120H (140H), and 190H (210H). Their thickness was 10T instead of 8T to accommodate the required parts. Conforming to the recent smartphones in landscape mode [41], the completely unrolled screen (height-to-width) aspect ratio for all prototypes was 1:2 (50H × 100W, 120H × 240W, and 190H × 380W; Fig. 2).

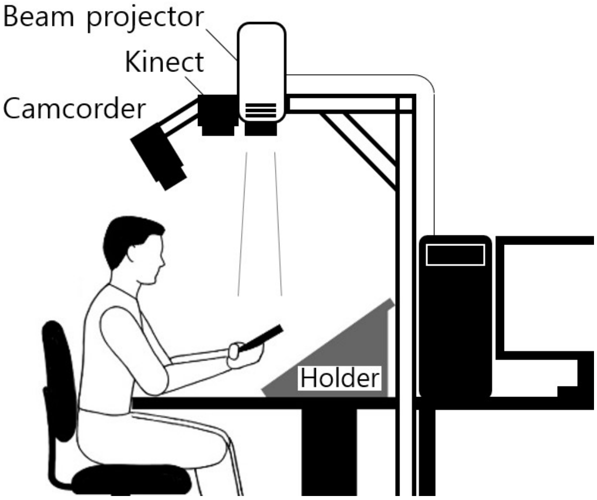


FIGURE 1. Experimental setting.

Three independent variables considered were screen height (Height), task type (Task), and hand length (Hand). Height was a three-level within-subjects factor (50H, 120H, and 190H). Task was a three-level within-subjects factor (web searching (Search), video viewing (Video), and e-mail composition (Mail)), three common tasks for both smartphones and tablet PCs [27]–[32]. Android default applications (Internet and Video) were used for Search and Video, and Gmail (Google, USA) was used for Mail. For Search, participants searched and read weather information; for Video, they watched a 10 s video (as in [42]); and for Mail, they typed ‘Thank you’ and pressed the ‘send’ button on the screen. Hand was a three-level between-subjects factor (HL_S, HL_M, and HL_L) corresponding to short ($\leq$16.3 cm, 10th percentile), medium (17.5–17.7 cm, 45th–55th percentile), and long ($\geq$18.9 cm, 90th percentile) hand lengths, respectively, to make the inter-group gaps 1.2 cm. The percentile values were based on the hand lengths of 20-to-50-year-old South Koreans [43].

For the performance of each task, five dependent variables were obtained – preferred screen width (mm), preferred screen width-to-height aspect ratio, user satisfaction, bi-manual gripping comfort, and gripping method. For the use of each prototype across the three tasks, two dependent variables were obtained – device portability and design attractiveness. User satisfaction for the performance of each task on a preferred-size screen was rated on a 100 mm visual analog scale (VAS; 0: very dissatisfied, 100: very satisfied). The perceived gripping comfort for the performance of each task on a preferred-size screen was rated on a 100 mm VAS (0: very uncomfortable, 100: very comfortable). Device portability in a completely retracted condition was rated on a 100 mm VAS scale (0: very poor, 100: very good). Design attractiveness was rated on a 100 mm VAS (0: very unattractive, 100: very attractive) considering the device form, screen size (including retracted, user-selected, and completely unrolled sizes),

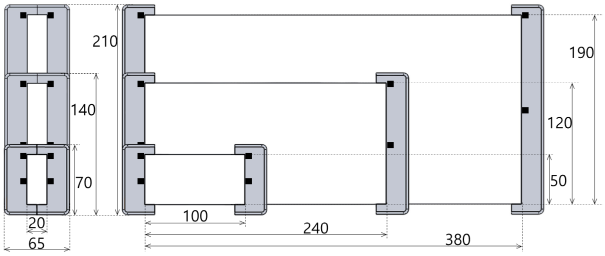


FIGURE 2. **Dimensions of three rollable-display device prototypes (unit: mm; left: completely retracted; right: completely unrolled). Three screen heights (50H, 120H, and 190H), one maximum screen width-to-height aspect ratio (2:1), and one device thickness (10T) were considered. Black squares (5 mm × 5 mm) on 22.5-mm wide side bezels (gray areas) indicate reflective markers.**

gripping comfort, and device portability. The recorded videos were analyzed to classify the gripping methods used for each task.

C. EXPERIMENTAL PROCEDURE

The practice session involved bimanually gripping each prototype and unrolling and rolling each screen 10 times, followed by a 1 min break. Nine treatments (3 Height × 3 Task) were then randomly presented to each participant. If necessary, the participants could use a 35° tilted tablet PC stand on the desk [39], [44]. The image on the screen was adjusted to the selected screen size for a given task in real time, and the selected screen width was recorded. To identify gripping methods, a video was recorded during the performance of each task. User satisfaction and gripping comfort were rated for a given treatment. After a 1 min break, the next random treatment was provided. After the nine treatments had been completed, the device portability and design attractiveness of each prototype were rated. These procedures took approximately 1 h per participant (Fig. 3).

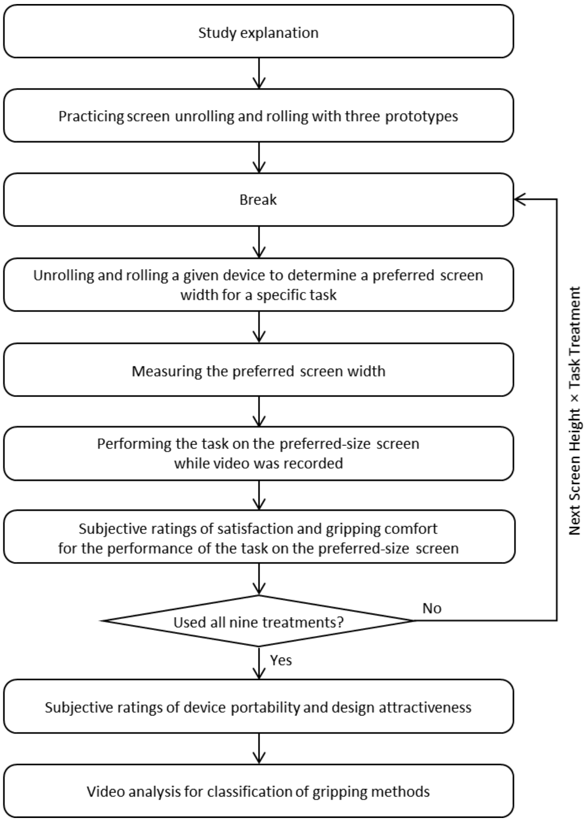


FIGURE 3. **Experimental procedure.**

D. STATISTICAL ANALYSIS

Three-way mixed factorial analysis of variance (ANOVA; screen height and task type: within-subjects factors, hand length: between-subjects factor) was conducted for preferred screen width, preferred screen aspect ratio, user satisfaction, and gripping comfort. Two-way mixed factorial ANOVA (screen height and hand length) was conducted for device portability and design attractiveness. When a main or interaction effect was significant, post-hoc pairwise comparison was performed using Tukey's honestly significant difference (HSD) test, with treatments showing greater or preferred results assigned to Group A. The 95th percentile and min-max range were obtained for the preferred screen width and preferred screen aspect ratio. Finally, the number of instances of using each gripping method was obtained to examine the effects of screen height, task type, and hand length on gripping method selection using Fisher's exact tests. JMP Pro$^{\text{TM}}$ (v12, SAS Institute Inc., NC, USA) was used for all statistical analyses, with significance concluded when $p < 0.05$.

III. RESULTS

A. INTERACTION EFFECTS OF HEIGHT × TASK

For the preferred screen width, the Height × Task interaction effect was significant ($p < 0.0001$; Table 1). Post hoc testing showed that the Height × Task treatments were statistically split into four groups (A-D; Fig. 4). Only 190H × Video was placed in Group A, exhibiting the widest mean (SE) preferred screen of 247.0 (9.4). Two treatments (50H × Mail and 50H × Video) were placed in the same group (D) as 50H × Search, which showed the narrowest mean (SE) preferred screen of 66.9 (3.7).

For the preferred screen aspect ratio, the Height × Task interaction effect was significant ($p < 0.0001$), with the Height × Task treatments split into four groups (A-D; Fig. 5). Four treatments (50H × Video, 120H × Video, 190H × Video, and 50H × Search) were placed in the same group (A) as 50H × Mail, which exhibited the highest mean (SE) preferred screen aspect ratio, 1.5 (0.07). Two treatments (120H × Mail and 190H × Mail) were placed in the same group (D) as 190H × Search, which exhibited the lowest mean ratio (SE) of 1.0 (0.06). Therefore, Video belonged to Group A across screen heights (mean (95th percentile) aspect ratio range = 1.30–1.5 (1.7–1.9)), and 50H belonged

TABLE 1. Effects of height, task, and hand on preferred screen width and aspect ratio, user satisfaction, and gripping comfort, and effects of height and hand on portability and design attractiveness.

Dependent variables	Statistics	Height	Task	Hand	Height × Task	Height × Hand	Task × Hand	Height × Task × Hand
Preferred screen width	p-value	**<0.0001**	**<0.0001**	**0.023**	**<0.0001**	**0.021**	0.29	0.49
	F ratio	$F_{2, 54}$ = 291.4	$F_{2, 54}$ = 18.86	$F_{2, 27}$ = 4.35	$F_{4, 108}$ = 11.02	$F_{4, 54}$ = 3.16	$F_{4, 54}$ = 1.28	$F_{8, 108}$ = 0.93
	Partial η^2	0.92	0.41	0.24	0.29	0.19	0.087	0.064
Preferred screen aspect ratio	p-value	**<0.0001**	**<0.0001**	0.067	**<0.0001**	0.37	0.25	0.14
	F ratio	$F_{2, 54}$ = 23.43	$F_{2, 54}$ = 12.62	$F_{2, 27}$ = 3.00	$F_{4, 108}$ = 8.12	$F_{4, 54}$ = 1.09	$F_{4, 54}$ = 1.39	$F_{8, 108}$ = 1.56
	Partial η^2	0.46	0.32	0.18	0.23	0.07	0.09	0.1
User satisfaction	p-value	**<0.0001**	0.089	0.21	0.47	0.95	0.95	0.89
	F ratio	$F_{2, 54}$ = 24.20	$F_{2, 54}$ = 2.53	$F_{2, 27}$ = 1.67	$F_{4, 108}$ = 0.90	$F_{4, 54}$ = 0.18	$F_{4, 54}$ = 0.17	$F_{4, 108}$ = 0.45
	Partial η^2	0.47	0.086	0.11	0.032	0.013	0.012	0.032
Gripping comfort	p-value	0.052	**0.0052**	0.55	0.41	0.28	0.85	0.34
	F ratio	$F_{2, 54}$= 3.12	$F_{2, 54}$= 5.81	$F_{2, 27}$= 0.62	$F_{4, 108}$= 1.01	$F_{4, 54}$= 1.30	$F_{4, 54}$= 0.34	$F_{4, 108}$= 1.15
	Partial η^2	0.1	0.18	0.044	0.036	0.088	0.025	0.078
Device portability	p-value	**0.0014**	-	0.60	-	0.69	-	-
	F ratio	$F_{2, 54}$= 7.46	-	$F_{2, 27}$= 0.53	-	$F_{4, 54}$= 0.56	-	-
	Partial η^2	0.22	-	0.037	-	0.04	-	-
Design attractiveness	p-value	**<0.0001**	-	0.95	-	0.58	-	-
	F ratio	$F_{2, 54}$= 35.8	-	$F_{2, 27}$= 0.05	-	$F_{4, 54}$= 0.73	-	-
	Partial η^2	0.57	-	0.0037	-	0.051	-	-

Note. Values of p less than .05 are in boldface.

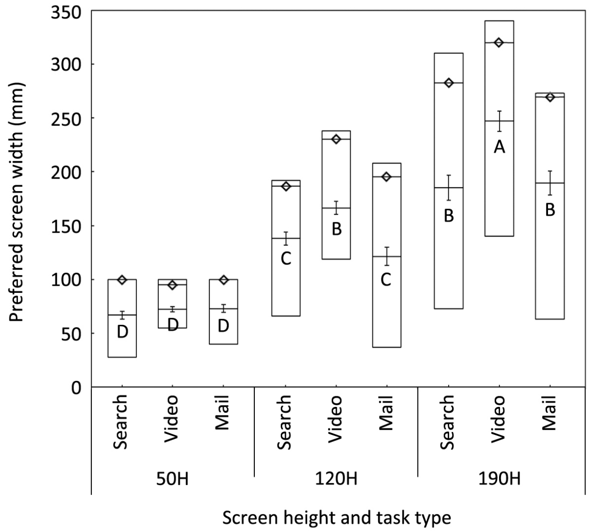


FIGURE 4. Effects of Height × Task on preferred screen width (min, mean, 95th percentile (diamond), and max values from bottom; letters A-D inside bars denote HSD grouping; error bars indicate SEs; SE range = 2.5-11.5).

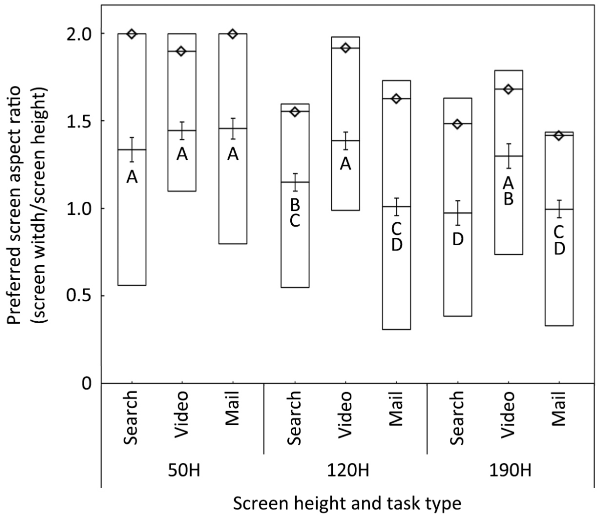


FIGURE 5. Effects of screen height × task type on preferred screen aspect ratio (min, mean, 95th percentile (diamond), and max values from bottom of each bar; letters A–D inside bars denote HSD grouping; error bars indicate SEs; SE range = 0.05–0.07).

to Group A across task types (mean (95th percentile) aspect ratio range = 1.3–1.5 (1.9–2.0)).

B. INTERACTION EFFECTS OF HEIGHT × HAND

The Height × Hand interaction effect on the preferred screen width was significant (p = 0.021), with its treatments split into five groups (A-E; Fig. 6). Only 190H × HL_L was placed in Group A, having the widest mean (SE) preferred screen of 235.5 (11.6). For 50H and 120H, the mean preferred screen widths were not significantly different across the three hand-length groups, whereas for 190H, the mean preferred screen of HL_L was significantly wider than those of HL_S and HL_M.

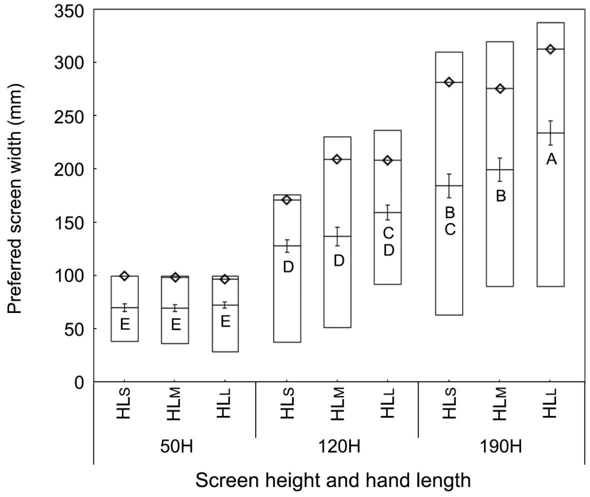


FIGURE 6. **Effects of Height × Hand on preferred screen width (min, mean, 95th percentile (diamond), and max values from bottom; letters A-D inside bars denote HSD grouping; error bars indicate SEs; SE range = 3.0-11.6).**

C. EFFECTS OF HEIGHT

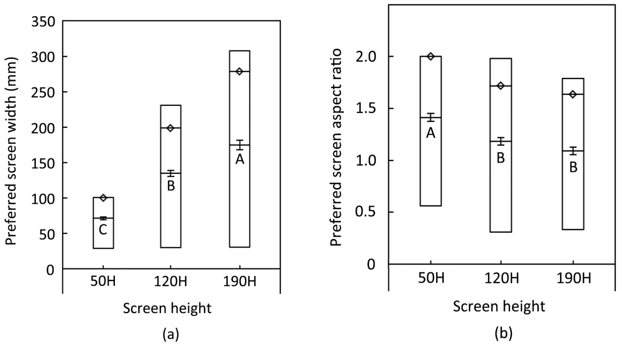
For the preferred screen width, the Height effect was significant ($p < 0.0001$), with its three levels split into three groups (190H, 120H, and 50H; Fig. 7a). For the preferred screen aspect ratio, the Height effect was significant ($p < 0.0001$), with its levels split into two groups (50H and 120H-190H; Fig. 7b). Based on the 95th-percentile values, 50H only required an aspect ratio of 2.0, whereas 120H and 190H required aspect ratios of 1.7 and 1.6, respectively. As the screen height increased, the preferred screen width increased, but the preferred screen aspect ratio decreased. For the user satisfaction, the Height effect was significant ($p < 0.0001$), with its levels split into two groups (190H-120H and 50H; Fig. 8).

The Height effects on the device portability ($p = 0.001$) and design attractiveness ($p < 0.0001$) were significant. Regarding the device portability and design attractiveness, the Height levels were split into two groups (120H-50H and 190H (Fig. 9a); 120H-190H and 50H (Fig. 9b)). Considering both device portability and design attractiveness, 120H was superior to 50H and 190H.

D. EFFECTS OF TASK

For preferred screen width (aspect ratio), the Task effect was significant ($p < 0.0001$), with its levels split into two groups (Video and Search-Mail; Fig. 10). The widest (highest) and narrowest (lowest) mean screen widths (aspect ratios) were observed with Video and Mail, respectively.

For the gripping comfort, the effect of Task was significant ($p = 0.004$), with its levels split into two groups (Video-Search and Mail; Fig. 11). The mean gripping comfort was lowest with Mail.



(a)

(b)

FIGURE 7. **Effects of screen height on (a) preferred screen width and (b) preferred screen aspect ratio (min, mean, 95th percentile (diamond), and max values from bottom of each bar; letters A-C inside bars denote HSD grouping; error bars indicate SEs; SE ranges = 1.9-6.8 for preferred screen width and 0.036-0.038 for preferred screen aspect ratio).**

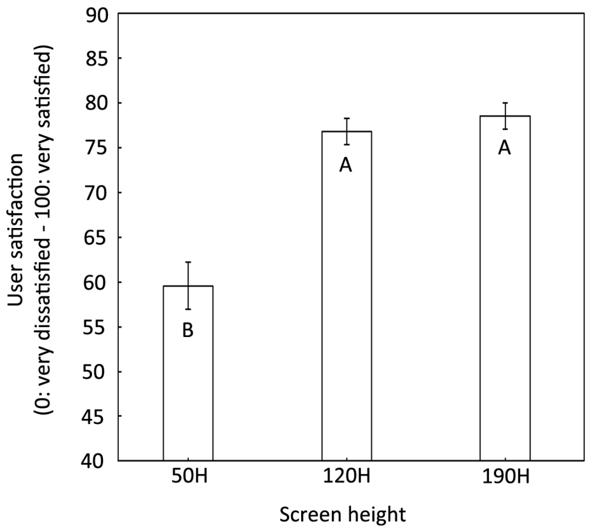
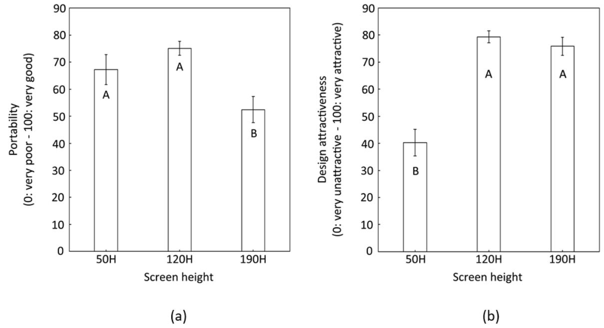


FIGURE 8. **Effects of Height on user satisfaction (letters A and B inside bars denote HSD grouping; error bars indicate SEs; SE range = 1.3-2.8).**



(a)

(b)

FIGURE 9. **Effects of Height on (a) portability and (b) design attractiveness (letters A and B inside bars denote post hoc grouping; error bars indicate SEs; SE range = 2.1-5.5 for portability and 2.2-4.9 for design attractiveness).**

E. EFFECTS OF HAND

The Hand effect was significant for the preferred screen width ($p = 0.023$), with its levels split into two groups (HL_L–HL_M

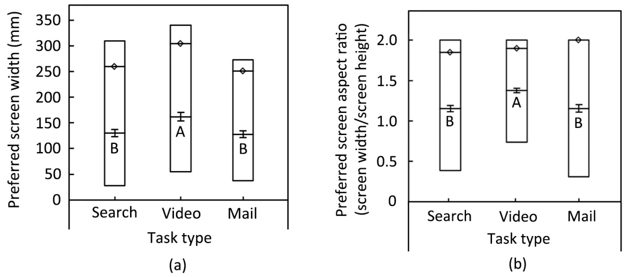


FIGURE 10. **Effects of Task on (a) preferred screen width and (b) preferred screen aspect ratio (min, mean, 95th percentile (diamond), and max values from bottom of each bar; letters A and B inside bars denote HSD grouping; error bars indicate SEs; SE range = 6.8-8.4 for preferred screen width and 0.03-0.04 for preferred screen aspect ratio).**

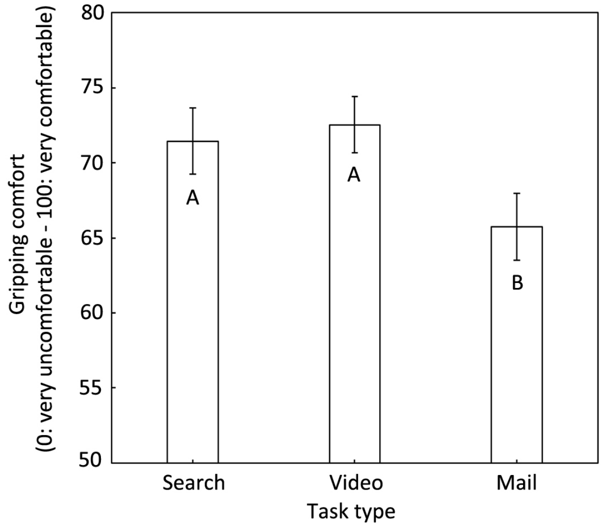


FIGURE 11. **Effects of Task on gripping comfort (letters A and B inside bars denote HSD grouping; error bars indicate SEs; SE range = 1.9-2.2).**

and HL_M–HL_S; Fig. 12). The mean preferred screen width was narrowest with HL_S.

F. GRIPPING METHODS

The gripping methods observed in this study were classified into four groups – $Grip_{Both}$, $Grip_{Left}$, $Grip_{Lower}$, and $Grip_{No}$ (Table 2). Fisher's exact tests for gripping method and each of Height, Task, and Hand were all significant ($p \leq 0.004$). $Grip_{Both}$ was most frequently used across Height, Task, and Hand, except for 190H. $Grip_{No}$ was most frequently used for 190H (Fig. 13). With increasing Height from 50H to 120H to 190H, the $Grip_{No}$ use frequency increased from 6.7% to 30.0% to 47.8% (Fig. 13).

IV. DISCUSSION

A. OVERVIEW OF HEIGHT, TASK, HAND, AND INTERACTION EFFECTS

Of the three significant main effects ($p \leq 0.023$) on the preferred screen width, Height (partial $\eta^2 = 0.92$) predominantly influenced the preferred screen width compared with Task (partial $\eta^2 = 0.41$) and Hand (partial $\eta^2 = 0.24$). Although the interactive effects of Height × Task and Height × Hand were significant ($p < 0.0001$), their contributions to the preferred screen width were relatively small (partial $\eta^2 =$ 0.29 and 0.19, respectively) compared with that of Height (Table 1 and Figs. 4–6).

Regarding the preferred screen aspect ratio, the effects of Height, Task, and Height × Task were significant. Height (partial $\eta^2 = 0.46$) was again a predominant factor compared with Task (partial $\eta^2 = 0.32$), Height × Task (partial $\eta^2 = 0.23$), and Hand (non-significant, partial $\eta^2 = 0.18$). Likewise, Height (partial $\eta^2 = 0.22$–0.57) predominantly influenced device portability and design attractiveness, compared with Hand (non-significant; partial $\eta^2 = 0.0037 - 0.037$).

B. INTERACTION EFFECTS OF HEIGHT × TASK

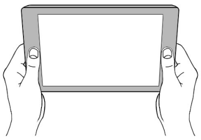
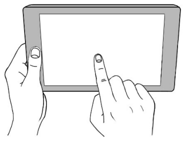
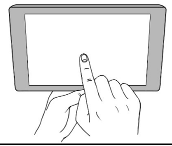
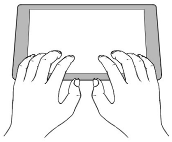
The mean preferred screen widths for the three tasks were not significantly different for 50H, whereas Video required higher mean preferred screen widths than Search and Mail for 120H and 190H (Fig. 4). A screen height of 50H showed higher mean preferred screen aspect ratios for all three tasks, belonging to Group A, which also included 120H × Video and 190H × Video (Fig. 5). The 95th-percentile preferred screen aspect ratios for the three tasks (Search, Video, and Mail) were 1.9-2.0 for 50H; 1.6-1.9 for 120H; and 1.4-1.8 for 190H, respectively. Therefore, 50H required a screen aspect ratio of up to 2.0, whereas 120H and 190H required a screen aspect ratio $<$ 2.0. For 120H and 190H, Video required higher screen aspect ratios (1.8–1.9) than the other two tasks.

C. INTERACTION EFFECTS OF HEIGHT × HAND

The significant interaction effect of Height × Hand on the preferred screen width can be explained by the Height effect alone for 50H and 120H (preferred screen width increased with Height), whereas 190H × HL_L yielded the widest preferred screen and was split from 190H × HL_M and 190H × HL_S. Thus, compared to the other two hand-length groups, the long-hand-length group preferred wider screens for 190H only, likely due to their wider thumb reach zone [45].

Across the hand lengths and tasks, the maximum (95th percentile) preferred screen aspect ratio range for 50H was 2.0 (1.9−2.0), reaching the maximum screen width provided by the 50H prototype (100 mm). Thus, 50H appears to have experienced a ceiling effect and may require a screen aspect ratio exceeding 2.0. For 120H and 190H, the maximum (95th percentile) preferred screen aspect ratio ranges were 1.98 (1.4−1.8) and 1.79 (1.5−1.7), respectively, indicating that a screen aspect ratio of 2.0 would be sufficient for these two screen heights.

TABLE 2. Classification and use frequency of gripping methods by height, task, and hand.

Factor	Level	Gripping methods			
		$\text{Grip}_{\text{Both}}$ (gripping both sides of the device with both hands for two-thumb input on the screen) 	$\text{Grip}_{\text{Left}}$ (gripping the left side of the device with left hand for right-index-finger input on the screen) 	$\text{Grip}_{\text{Lower}}$ (holding the bottom of the device with left hand for right-index-finger input on the screen) 	Grip_{No} (placing the device on the table for two-hand input on the screen) 
Height	50H	51	32	1	6
	120H	40	15	8	27
	190H	35	7	5	43
Task	Search	46	25	4	15
	Video	35	20	8	27
	Mail	45	9	2	34
Hand	HL_{S}	39	15	1	35
	HL_{M}	44	18	11	17
	HL_{L}	43	21	2	24

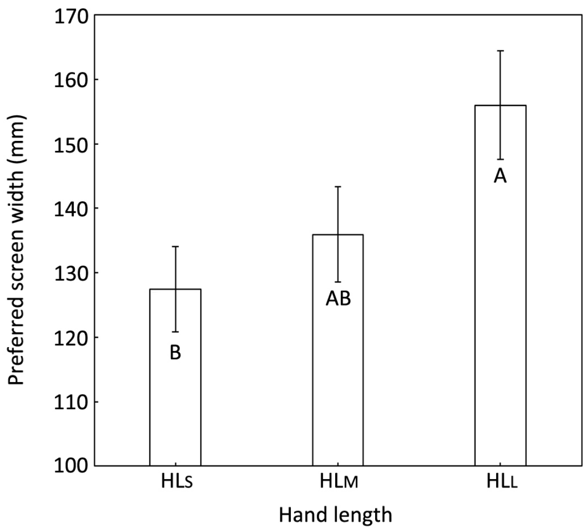


FIGURE 12. Effects of Hand on preferred screen width (letters A and B inside bars denote HSD grouping; error bars indicate SEs; SE range = 6.6–8.4).

D. EFFECTS OF HEIGHT

The preferred screen width increased with screen height (Fig. 7), whereas the preferred screen aspect ratio was the highest for 50H, which was split from 120H and 190H. The 95th-percentile screen aspect ratio for 50H was 2.0. Presumably, the participants completely unrolled the 50H screen to overcome its small screen size.

If user satisfaction, device portability, and design attractiveness are considered simultaneously, 120H appears to be desirable; 190H and 120H yielded higher user satisfaction than 50H; 120H and 50H yielded higher device portability than 190H; and 120H and 190H yielded higher design attractiveness than 50H.

The usage frequency of Grip_{No} increased with Height. As the display size increases, the display area that the thumbs cannot reach increases, making $\text{Grip}_{\text{Both}}$ inappropriate. Similarly, the uni-manual gripping methods ($\text{Grip}_{\text{Left}}$ and $\text{Grip}_{\text{Lower}}$) do not appear to be useful for 190H.

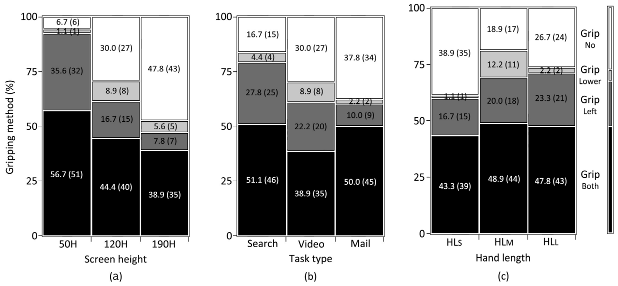


FIGURE 13. Gripping methods by (a) screen height, (b) task type, and (c) hand length (the number within a cell is the percentage (number) of participants selecting a particular gripping method for each level of height, task, and hand).

E. EFFECTS OF TASK

Video required the widest screen and highest screen aspect ratio. Screen touch input does not occur frequently during video viewing, which may have contributed to the selection of wider screens. For Search, which involved reading a news article, wider screens may have been advantageous (e.g., providing more information at once and requiring less scrolling; [5], [6]) as well as disadvantageous (e.g., reducing legibility due to difficulty in locating next lines; [13]). When on-screen interactions are required and $\text{Grip}_{\text{Both}}$ is selected, the screen width is likely to be restricted by the two-thumb reach zone. For Mail, 50% of participants (45/90) used $\text{Grip}_{\text{Both}}$. Of the three tasks, Mail provided the lowest gripping comfort, presumably because this task involved more keystrokes than the other two tasks, and rollable screens would have provided relatively lower reaction forces to finger strokes during screen touch compared with non-flexible displays. As e-mailing is the most frequent task performed on tablet PCs [46], further investigation is warranted to design tablet PC-size rollable display devices that can provide sufficient force feedback to fingers and improve gripping comfort during touch interactions.

F. EFFECTS OF HAND

In this study, wider screens were preferred as hand lengths increased. When using smartphones, the thumb-reach zones of individuals with longer hands are wider [25], [47], [48], and there is a positive correlation between hand and thumb lengths [45]. Therefore, the preference for wider screens observed in the group with longer hands is likely due to their wider thumb-reach zones. Notably, the mean preferred screen aspect ratios of the three Hand groups were not significantly different. Therefore, the group with longer hands preferred wider screens, but not as much as their mean preferred screen aspect ratio is significantly different from those of the other two groups.

G. GRIPPING METHODS

Gripping methods are affected by smartphone tasks [24]. The 120H and 190H prototypes considered herein correspond to the typical heights of tablet PCs in landscape and portrait modes, respectively. To the knowledge of the authors, the gripping methods used for tablet PCs have not been reported, although these are likely to include $\mathrm{Grip}_{\mathrm{Both}}$, $\mathrm{Grip}_{\mathrm{Left}}$, $\mathrm{Grip}_{\mathrm{Lower}}$, and $\mathrm{Grip}_{\mathrm{No}}$ observed in this study. Of these four gripping methods, $\mathrm{Grip}_{\mathrm{Both}}$ was commonly assumed in the previous tablet PC touch interaction studies (e.g., [35], [49]–[51]). As the remaining three gripping methods can be used during tablet PC touch interactions, a comparative study of conventional and rollable-screen tablet PCs is warranted to examine the potential differences in gripping methods due to display type-related differences and the relevance of these differences to easy device operation and other UX elements.

H. LIMITATIONS AND FUTURE WORK

There were limitations in this study. First, a 10 s video was considered for video viewing although the viewing durations used in previous display evaluation studies vary from 10 s to 4 h [42], [52]–[59]. As video viewing usually lasts for longer periods of time, it is necessary to examine the effects of long-term video viewing on rollable display size requirements. Second, the email composition task involved very short typing. It is thus necessary to complement this task, for example, by using pangram [17] or consider other typing tasks (e.g., instant messaging). Third, the spring force to retract a completely unrolled screen was fixed at 2.5N in this study. Although this force level is sufficiently high considering the light weight of rollable screen (a 5.7″ rollable screen weighs approximately 5 g), it is still necessary to consider diverse spring force levels because the gripping method and gripping comfort could be affected by the required pulling force [60]–[62]. Fourth, although the user satisfaction ratings presumably reflected the performance of the three tasks considered in this study, direct task performance measures (e.g., typing speed) were not used. Fifth, determining appropriate rollable-screen sizes for diverse touch interaction methods (e.g., pinch zoom or drawing with a stylus pen) is necessary. Sixth, only younger individuals were considered. The screen sizes preferred by older individuals may differ due to age-related changes (e.g., reduced joint range of motion and different needs for legibility). Seventh, only South Koreans were considered, although each ethnic group has distinct hand anthropometric dimensions [63], [64]. Eighth, the gender ratios differed across the three hand-length groups, which is typical. Although male hands are longer than female hands on average [43], [65], recruiting two gender groups with comparable hand sizes may be necessary to examine gender-related effects on the seven UX elements considered herein and other UX elements while effectively controlling the difference in hand size between the two gender groups.

V. CONCLUSION

This study examined the effects of Height, Task, and Hand on the seven UX elements associated with the use of mobile rollable-display devices, with the ultimate objective of identifying ergonomic rollable-display device design requirements. Height had a greater impact on determining the preferred screen width over Task and Hand. Of the three screen heights considered, 120H yielded the most significant improvement in the overall UX, consequently recommending 120H × 206W to accommodate diverse tasks and user needs. Finally, considering the reduced gripping comfort and greater adoption of $\mathrm{Grip}_{\mathrm{No}}$ with increasing screen size, rollable-display devices should provide sufficient screen reaction force to finger strokes.

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