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VISUAL SEARCH ON A MOBILE DEVICE WHILE WALKING

A Thesis
Presented to
The Faculty of the Department of Industrial and Systems Engineering
San José State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Ji Jung Lim
May 2012

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The Designated Thesis Committee Approves the Thesis Titled

VISUAL SEARCH ON A MOBILE DEVICE WHILE WALKING

by

Ji Jung Lim

APPROVED FOR THE DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING

SAN JOSÉ STATE UNIVERSITY

May 2012

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ABSTRACT

VISUAL SEARCH ON A MOBILE DEVICE WHILE WALKING

by Ji Jung Lim

Previous studies have examined the effects of walking and user interface elements on mobile task performance, using physical target selection tasks. The current study investigated the effect of walking and user interface elements on visual search on a mobile device, isolating the effects on perceptual and cognitive processes. The effects of object size, contrast, and target location on mobile devices while walking and standing were examined. A serial visual search using “T” and “L” shapes on a mobile device, which controlled for physical target selection involvement was conducted. The results showed that walking, bigger object size, and the target position in the outer area of the mobile device display slowed the visual search response time. This suggests that walking causes a negative performance effect not only on the physical task but also on the cognitive process while interacting with the mobile user interface. In addition, the results of the study suggest that the placing of major content and call-to-action items in the inner area of the display are likely to improve task performance on a mobile device.

DEDICATION

I would like to dedicate my thesis to my father, Dr. In Bae Kim (1948 – 2011), who taught, encouraged, supported, and guided me for all my life. What he taught and showed me has become the foundation of my life. I would like to thank him for helping me to grow as a professional and educated individual. I believe that he is happy and proud of me right now.

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I would also like to thank my mother Won Sook Lee for her daily prayers, support, and help throughout the last three years. My appreciation goes to my family and friends who have supported and encouraged me to complete this research, especially Long Ngo, Nasson Boroumand, and Seong Ah Byeon, who supported my thesis process.

Finally, I would like to give special thanks to my husband, Dae Lim, my daughter, Kate, and my son, Elliot. Their support, patience, encouragement, and smiles have motivated me throughout the graduate program and thesis research process.

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Chapter 1 Introduction

1.1 Safety Concern Increase with Increased Smartphone Usage

Smartphones that support multi-touch inputs have become ubiquitous as hand-held computing devices have become more prevalent since the iPhone was released to the market in 2007 (Honan, 2007). The smartphone market has been the fastest growing segment in the mobile phone market for the last 4 to 5 years. According to a mobile market research report by ComScore in 2010, there were 45.5 million smartphone subscribers out of a total of 234 million cell phone subscribers in the United States (ComScore, 2010). Moreover, a digital media research firm Berg Insight reported in 2011 that global shipments of smartphones had increased 74% from 2009 to 2010 (BergInsight, 2011). Berg Insight also predicted that there would be 2.8 billion smartphone users globally by 2015.

Smartphones and 3G / 4G (fast) mobile wireless networks have increased the usage of advanced functions (i.e., web surfing, emailing, text messaging, picture and video taking, etc.) on smartphones that used to be major functions on computers. These mobile wireless networks have enabled even faster communication among smartphone users. Because of the fast communication trends, immediate responses while using a smartphone are generally expected nowadays. Thus, advanced function usages on the smartphone while walking are witnessed every day on the street. This trend has raised a safety concern as the number of people sustaining injuries while using their mobile phones has increased. Running into objects or people, falling into manholes, or stepping into puddles have caused people injuries and inconvenience, and because of the numbers of injuries, the numbers of phone use accidents are often reported in the media (Richtel, 2010). According to Richtel (2010), the number of injuries associated with pedestrian cell phone usage has increased over recent years. The number of pedestrian emergency room visits in 2007 for the same reason doubled compared to 2006, and that happened again in 2008. More than 1000 pedestrians visited US emergency rooms in 2008 because of cell phone use-related injuries. Hatfield and Murphy (2007) reported that pedestrians who crossed the street while talking on the phone walked much more slowly and were much less attentive to the road situation or traffic than the pedestrians who crossed without using a mobile phone. Hatfield and Murphy's research suggested that using a mobile phone while crossing roads creates unsafe pedestrian behaviors.

Numerous studies after Hatfield and Murphy's study confirmed that people experienced significant cognitive distractions while using their phone and crossing the street. This cognitive distraction of mobile phone users on roads decreased situation awareness and thus increased unsafe behaviors and the risk of accidents and injuries regardless of pedestrian gender or age (Hyman, Boss, Wise, McKenzie, & Caggiano, 2010; Nasar, Hecht, & Wener, 2008; Stavrinos, Byington, & Schwebel, 2009).

1.2 Mobile User Interface Design Solutions to Mitigate the Safety Concerns

In spite of this astonishing growth of smartphone usage and safety issues, not much has been studied in the way of mobile user interface design solutions to reduce cognitive workloads and enable successful multi-tasking on a mobile device while walking.

Presumably, in a walking condition, information-processing abilities would be decreased, and cognitive workload would be increased because of dual tasking (i.e., reading while walking or searching while walking) or multitasking (i.e., reading, searching, selecting a target while walking) (Ophir, Nass, & Wagner, 2009).

Well-designed mobile interfaces using the effective visual search attributes such as color, brightness, or size may improve the visual search performance on mobile devices as well as the ability to walk and use a smartphone. In the current study, the performance of visual searches (i.e., searching for targets among distractors) was examined. Visual search, which consists of perceiving and searching for information on display, would be the very first task among any other major tasks such as menu navigation or text input. A more efficient visual search process may reduce user's cognitive workload for the tasks on a mobile device and mitigate safety concerns. To measure mobile user information processing abilities while walking, a conventional serial visual search paradigm was used; participants were instructed to search for a target ("T" shape) among distractors ("L" shapes) in different rotated orientations (Wolfe & Horowitz, 2004). This visual search paradigm was used to reduce the effects of other variables that are not relevant to the current study such as reading abilities or color preference. The differences in cognitive workloads between mobile device users in a walking condition and those in a standing condition were measured using a workload self-assessment questionnaire.

In addition, visual search accuracy per target location on a mobile device was evaluated to understand the effects of the target location on visual search performance. Mobile user interface designs with the optimal target location were expected to reduce visual search time and increase accuracy. The effects of object size, object contrast, and location on a mobile device were expected to lead to mobile user interface design solutions that reduce cognitive workloads, allow for efficient task completion on mobile devices, and alleviate safety issues of using mobile devices while walking. The findings of the current study may answer the mobile user experience or user interface designer’s everyday questions like where to place alerts or call-to-action buttons on a mobile display.

Chapter 2 Related Work

2.1 Smartphone Usage While Walking

Many studies have documented a negative performance effect on target selection and reading on a mobile device while walking. Schildbach and Rukzio (2010) examined target selection and reading performance on a mobile phone and confirmed the negative performance effects of walking on target selecting and reading on a mobile phone. Kane, Wobbrock, and Smith (2010) suggested that the negative performance effect of walking was caused by many different environmental factors such as vibration, light, glare, noise, weather, temperature, or uneven terrain, attentional factors such as physical obstacles, distraction, or social interaction, or physical factors such as clothing, occupied hands, baggage, user fatigue, or user or device movement. To compensate for the negative performance effects of mobile phone usage while walking, mobile user interface design solutions (i.e., adding bigger buttons, providing a walking mode of user interface, etc.) have been suggested in previous studies (Kane et al., 2008; Schildbach & Rukzio 2010).

2.2 Reading While Walking

Vadas. Patel, Lyons, Starner, and Jacko (2006) investigated reading performance on a mobile device while walking. Vadas et al. (2006) reported that walking led to decreases in reading accuracy, increases in mental workload, and increases in stress levels compared to stationary usage. Studies by Schildbach and Rukzio (2010) found that increasing target size could not compensate for the negative performance effect of walking over a reading task. This was because a larger text requires more scrolling on a mobile phone.

2.3 Target Size on a Mobile Device

Hasegawa, Miyao, Matsunuma, Fujikake, and Omori (2008) examined the text font size effect on legibility in a mobile display and reported that legibility was higher with larger characters (2.5 mm height) than medium (2.0 mm height) or small (1mm height) characters. Decreasing the character sizes resulted in an increase of subject evaluation on legibility and error rate, and a decrease of viewing distance.

Lin, Goldman, Price, Sears, and Jacko (2007) examined the effect of target size, walking speed, and walking difficulties on stylus-based tapping performance and validated the effectiveness of Fitts' Law on mobile phone usage while walking (Fitts, 1954). Fitts' Law is a classic human computer interaction principle, which defines the correlation between movement time, target size, and distance between the starting point to the center of the target. That is, the movement-time increases when the target size decreases and the distance to the target increases. Lin et al. (2007) reported that walking increased the task completion time, error rates and cognitive workloads of target selection tasks on mobile phones. They also examined the effect of target sizes 1.9mm to 6.4 mm in diameter, and found that a larger target size decreased the error rate and the selection time in all the following conditions: seating, slow walking, fast walking, and walking in an obstacle course. Lin et al. (2007) reported that Fitts' Law was effective for all conditions.

Lin et al. (2007) used a wide range of target sizes (1.9mm to 6.4 mm). In the current study, two different target sizes were used, 6.74mm and 9.5 mm, which are larger than the target sizes Lin et al. (2007) used in their study and are now commonly used in mobile phone user interfaces. The object sizes used in the current study are the actual size of application icons and menu icons on the Android phones. Lin et al. (2007) suggested that the target size 6.4mm condition maintained an error rate of less than 10% for the obstacle course condition. Park, Han, Park, and Cho (2008) reported that 7mm and 10mm target size performed better than 4mm in their target selection study. The two object sizes used in the current study are thus good object sizes to examine the interaction between object size, object contrast, target location, and the walking condition on a mobile user interface.

2.4 Target Contrast During Visual Search on a Mobile Device

Schaik and Ling (2001) studied the effect of contrast on a visual search on a computer display. Black (#000, hexadecimal color code in HTML and CSS) on grey (#BBB) with a contrast ratio of 10.94:1 and white (#FFF) on grey (#BBB) with a contrast ratio of 1.92:1 were compared, but were not found to differ. Hasegawa, et al. (2008) examined the effect of display contrast on legibility on mobile phone screens, however, there was no effect found. Hasegawa, et al. (2008) used meaningless text to measure the legibility, and performed only in a sitting condition. Although the previous studies did not find the effect of contrast either on a computer display nor a mobile device while sitting, it is unknown whether contrast has an effect on a mobile device display while walking. In the current study, the contrast effect on a mobile display while walking with a conventional visual search paradigm excluding all irrelevant factors such as reading ability, character familiarities, etc. was examined.

2.5 Visual Search on a Mobile Device

There are so many features to interact with and so much information to read on mobile devices. Activities such as image browsing, text messaging, reading, and gaming, on a mobile device screen consistently occur in people's busy lives. All activities on mobile devices always involve visual search processes at the beginning because the user needs to search for objects such as icons, photos, videos, and texts, to perform any tasks. Previous studies (Hasegawa et al., 2008; Lin et al., 2007; Schildbach & Rukzio, 2010; Vadas et al, 2006) examined the performance of reading or physical target selection rather than the visual search process that involves cognitive activities.

In Lin et al.'s (2007) study, a single target was displayed at a time and participants needed to select the actual target by tapping on a display. This task involved not only visual perception by users but also physical targeting activities of using a mobile phone. The primary focus of the current study was to analyze the visual perception and cognitive activities of users on a mobile device display using a conventional visual search paradigm [i.e., searching for the target ("T" shape) among distractors ("L" shapes)]. To control the physical targeting process, which is unrelated to focus of the study, the selection buttons were separated from the actual visual search objects (target and distractors) and remained at the same location.

2.6 Target Location During Visual Search on a Mobile Device

Lin et al. (2007) discovered that, consistent with Fitt's Law (Fitts, 1954), target size and distance to the target affect target selection by tapping on a mobile display while walking around obstacles. Park et al. (2008) recommended using the center area of a mobile display for the general input elements because the results of their target selection performance study suggested that the center area of the mobile display provides higher pressing convenience, fair success rates, and fewer errors than the outside of the mobile display.

Since visual attention begins at the previous target location, the visual attention shifting from the previous target location to the subsequent target location likely affects the task completion time. The center (inner) area of the display is more likely closer to the previous target location than the outer area of the display. Thus, a higher performance rate (less response time and lower error rate) at the center (inner) area of the mobile display was expected in the current study, consistent with the findings of the study by Park et al. (2008).

2.7 Visual Attention During Visual Search on a Mobile Device

Many studies regarding eye tracking on desktop computers have been done to understand users' visual attention movement and gazing dwell time while interacting with the computer user interface. The findings of these studies have been applied to user interface design strategies. Compared to the eye tracking studies on desktop computers, eye tracking on mobile phones has not often been done. One reason may be that the history of smartphones is much shorter than the history of desktop computers. Another reason could be an inaccuracy of the eye tracking measurement. It is very difficult to measure users' gazing points and eye movement accurately on mobile phones because of the small sized display, the frequent head movement, and the jitter of the eye fixation while holding a mobile phone (Drewes, Luca, & Schmidt, 2007; Nagamatsu, Yamamoto, & Sato, 2010).

In the current study, a visual search paradigm was used to measure users' visual attention, behavior, and perception on a mobile device display, while avoiding the drawbacks of eye tracking technology. The target location on a 4 by 6 grid display was manipulated to examine which area of the display got more attention and accuracy on target detection. To avoid the physical targeting aspect of visual search activities and measure the perception process only on a mobile device display, selection buttons are located in a consistent location rather than physically pressing on the target location (see Figure 1).

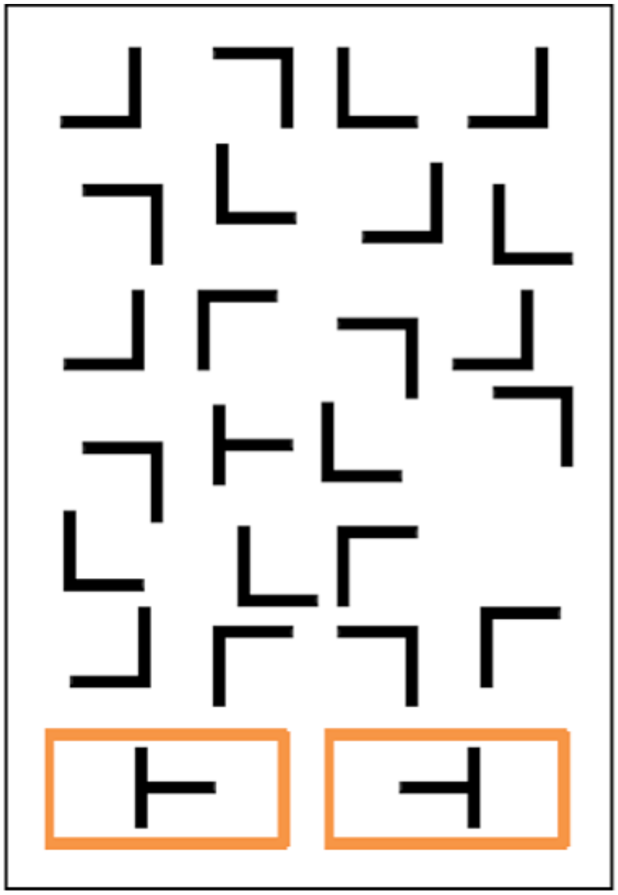


Figure 1. Target and distractors on the mobile display for the visual search performance task.

2.8 The Current Study

Previous studies have discovered visual information processing impairments while walking; however, few comprehensive user interface design solutions for mobile devices have been proposed. In the current study, negative effects on mobile device usage performance while walking was compared with stationary usage. The effects of visual search attributes, object contrast and size were examined to assess which attributes can compensate for the negative performance effect of mobile device usage performance in a realistic walking simulation. In addition, the target location on a mobile device user interface was investigated to understand the mobile user's visual focus of attention on a mobile device display.

The effect of object size, object contrast, and target locations on the mobile user interface can be used as guidelines for mobile user interface design solutions to improve performance. For example, mobile design questions like where to place the alerts or call-to-action buttons can be answered with the current study findings.

Chapter 3 Hypotheses

3.1 Hypotheses

H1. Smaller object size decreases visual search performance on a mobile device.

H2. Walking decreases visual search performance on a mobile device.

H3. Targets in locations near the center (inner area) of the display improve search performance more than targets in outer locations.

Chapter 4 Method

The current study was aimed to understand the effects of object size and object contrast during the visual search performance while using a mobile phone in the walking and standing conditions. In addition, the study examined the effects of the target location. The experiment was conducted on an indoor test track.

4.1 Participants

Twenty-nine females and males participated in the study for university class credit. Based on the Power analysis, 33 participants were recruited, but four participants' data were excluded because of their vision condition. Participants were at least 18 years old. Participants who owned a mobile phone (either feature phone or smartphone) and had normal or corrected-to-normal vision were recruited. During recruitment, there were no restrictions with respect to handedness.

4.2 Experimental Design

A within-subjects design was used. The experiment was divided into two blocks. One block was conducted in a walking condition, and the other block was conducted in a standing condition. The order of the conditions for the blocks was counterbalanced. Half of the participants performed the walking condition for the first block and the standing condition for the second block, and vice versa for the other half of the participants.

4.2.1 Visual search task. A visual search performance task using the shapes “T” and “L” was conducted. The mobile phone screen displayed the target “T” shape in two different orientations; the top of the “T” shape faced either right or left. There were multiple “L” shapes as distractors in four different orientations; the top of the “L” shapes faced top, right, bottom, and left. Combinations of one target and between 20 and 23 distractors were displayed in a 4 by 6 grid (see Figure 1). The number of “L” shapes was randomly chosen on each trial. Participants performed the visual search tasks by searching for the target “T” and selecting either ⊢ or ⊣ button based on the orientation of the target on the screen.

4.2.2 Independent variables. The first independent variable, *object* (target and distractors) *size*, had two levels, small and large. The small target font size was 6.74 x 6.74 mm. The large object size was 40% larger in height and width, 9.5 x 9.5 mm (see Figure 2). The cell size of the 4 by 6 grid remained the same.

Figure 2. Two different object sizes.

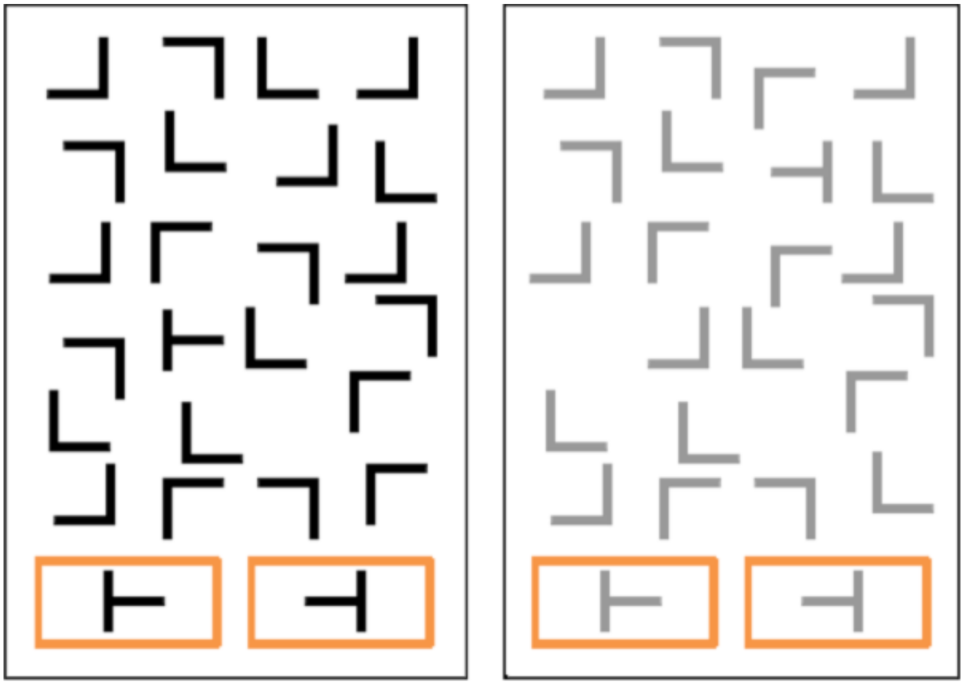
The second independent variable, *object contrast,* had two levels high and low. The high contrast (contrast ratio: 21.00:1) showed a black (Web color: #000) target on a white

(Web color: #FFF) background and low contrast (contrast ratio: 2.85:1) showed a light gray (Web color: #999) target on a white (Web color: #FFF) background (see Figure 3).

Figure 3. Two different object contrasts (approximate).

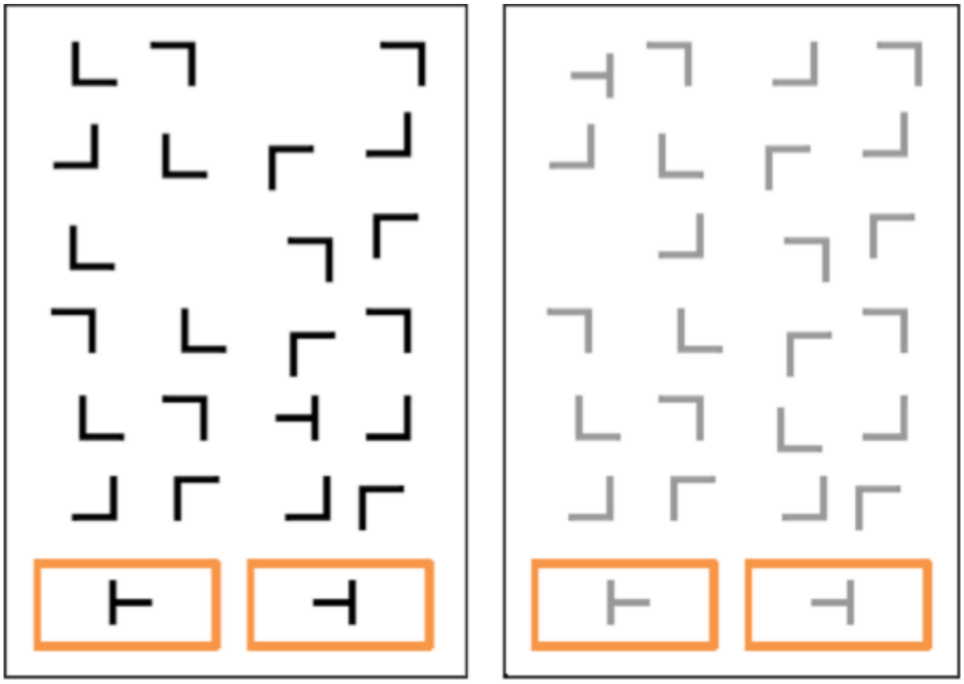
In each trial, the mobile screen displayed one of the four different array types in a random order. The four different array types were Type A: Large font size and High contrast, Type B: Large font size and Low contrast, Type C: Small font size and High contrast, and Type D: Small font size and Low contrast (see Figure 4). On any given trial, the target and all the distractors had the same size and contrast.

A single object (either a target or distracter) was presented in each cell of the 4 by 6 grid. A jitter, between 0 to 3 pixels in 4 different directions (top, down, left, and right), was randomly applied for each object.



Type A : Large font size + High contrast

Type B : Large font size + Low contrast



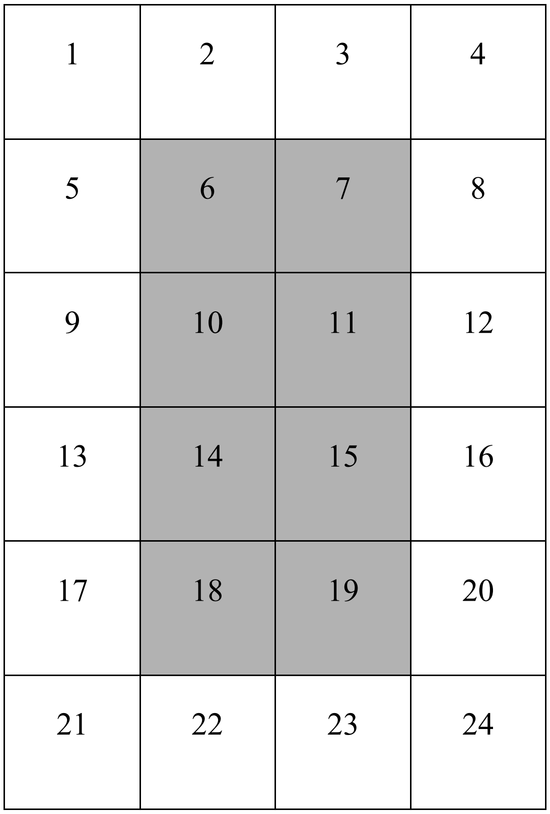
Type C : Small font size + High contrast

Type D: Small font size + Low contrast

Figure 4. Four different array types.

The third independent variable was *walking* condition. Half of the participants were walking while performing the visual search performance test on a mobile phone in the first block, and standing while performing the trials in the second block. The other half of the participants were standing while performing the trials in the first block and then walking in the second block to counterbalance the order of the walking and standing conditions.

The fourth independent variable was *target location*. A single target was randomly presented in one of the 24 grid cells in each trial. Each cell was assigned a unique ID to inspect the center (inner) area of the mobile device display (ID 6, 7, 10, 11, 14, 15, 18, and 19), which was the second and third columns in the second through fifth rows in a 4 x 6 grid (see Figure 5).



1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16
17	18	19	20
21	22	23	24

Figure 5. 4x6 grid locations on the mobile display, with the inner area colored gray and the outer area colored white.

4.2.3 Materials. A Motorola Droid 2 phone with a resistive touch-screen and Android operation system was used during the study. The visual search prototype application was implemented using Flex and Adobe Air (see Figure 6).

Figure 6. Visual search trial application on the mobile device used.

4.2.4 Test track. To simulate a real life visual searching situation while walking, a non-linear, oval shaped track around obstacles (i.e., machines, chairs, etc.) was designed in a 7.93m x 16.98m indoor lab (see Figure 7). In order to reduce the learning effects of the environment (possibility of memorization), participants were asked to walk on the track in two different directions: clockwise and then counter-clockwise around obstacles until the block was completed. The 46.08m-length track was drawn on the lab floor around obstacles.

To avoid possible injuries during the experiment, all the obstacles' corners were padded, and participants were allowed to walk around the track before the experiment to get acquainted with the environment.

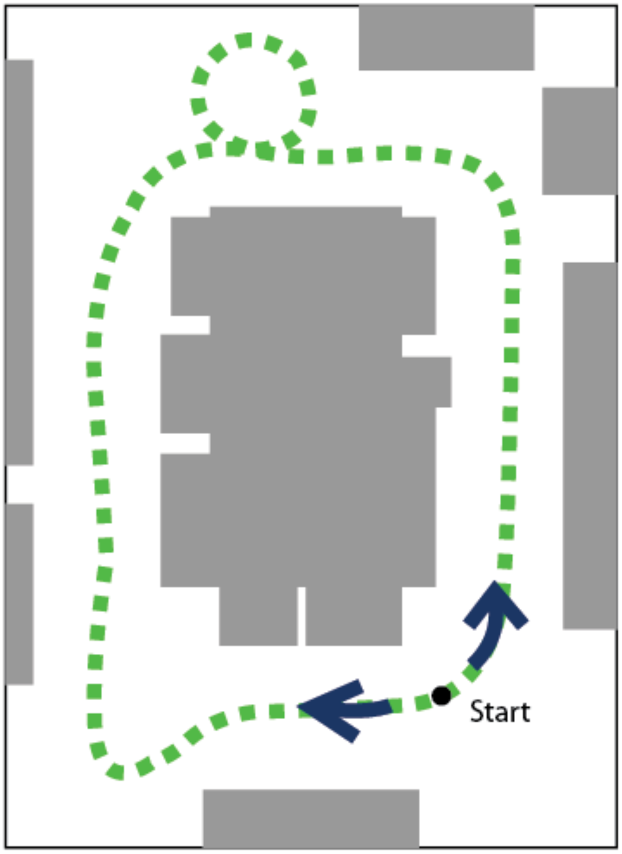


Figure 7. The test track layout in the indoor lab with obstacles marked with solid sections and the test track marked with a dotted line.

4.2.5 Dependent measures.

4.2.5.1 Quantitative measures. To measure the visual search performance, response time (RT) and error rate (ER) were used. The data of the target selection (correct and wrong) and response time (ms) were recorded automatically. All participants performed two blocks of visual search trials, one while standing and the other one while walking. Each block consisted of 300 trials including one practice trial.

Measuring the mental workload of each user is essential to evaluate the effects of user interface design improvement. To assess the workload and performance of participants, all participants were asked to fill out a self-report questionnaire after each block. The questionnaire included the workload self-assessment questions regarding visual search performance and emotional responses that were borrowed and modified from NASA Task Load Index (TLX) (NASA Ames Research Center, 1987). In the workload self-assessment questionnaire, mental demand, physical demand, temporal demand, performance, effort, and frustration were measured on 5-point scales (see Figure 8).

Mental Demand How mentally demanding was the task?	Very low 5 – 4 – 3 – 2 – 1 Very high
Physical Demand How physically demanding was the task?	Very low 5 – 4 – 3 – 2 – 1 Very high
Temporal Demand How hurried or rushed was the pace of the task?	Very low 5 – 4 – 3 – 2 – 1 Very high
Performance How successful were you in accomplishing what you were asked to do?	Perfect 5 – 4 – 3 – 2 – 1 Failure
Effort How hard did you have to work to accomplish your level of performance?	Very low 5 – 4 – 3 – 2 – 1 Very high
Frustration How insecure, discouraged, irritated, stressed, and annoyed were you?	Very low 5 – 4 – 3 – 2 – 1 Very high

Figure 8. Workload self-assessment 5-point scales.

4.2.5.2 Qualitative measures. The experimenter recorded participants' walking errors such as bumping into obstacles or having to readjust direction to observe the track changes.

4.2.6 Procedure. Prior to the experiment, participants confirmed their normal or corrected-to-normal vision and mobile phone ownership. Participants listened to visual search task instruction and track layout details. The instructions included walking direction details (alternating direction: clockwise and then counter-clockwise) and walking speed (walking in a normal walking speed) for the walking block. Participants were also instructed to use two hands: one hand for holding a phone and the other hand for selecting one of the buttons. The auto- rotation feature on the mobile phone was turned off during the study to ensure the screen displays in a vertical orientation only. Before the walking block, participants were asked to walk one lap around on the track in their normal walking speed to compare their normal walking speed and their walking speed during the visual search trials.

Figure 9. Visual search trial while walking in the lab on the track marked with a dashed line.

In the first block, participants performed the visual search trials either while walking or standing. In the second block, they performed the trials on a mobile phone in the opposite condition.

After each block, participants filled out a post-block questionnaire, including a workload self-assessment questionnaire (see Appendix A). Participants also filled out the post-experiment questionnaire (see Appendix B) regarding daily personal phone usage at the end of the experiment.

Chapter 5 Results

5.1 Response Time

The mean response time was calculated for each participant in each of the sixteen conditions and was submitted to a 2 (walking condition) x 2 (object size) x 2 (contrast ratio) x 2 (location) analysis of variance (ANOVA). Trials with incorrect responses were excluded from the data.

There was a significant main effect of the walking condition on the response time, $F(1, 28) = 20.02$, $p < .001$. The mean response time of the walking condition ($M = 1957.29$ ms, $SD = 398.44$ ms) increased by 19.29% over the standing condition ($M = 1640.78$ ms, $SD = 334.22$ ms).

There was a significant main effect of the object size on the response time, $F(1, 28) = 14.02$, $p < .01$ (see Figure 10). On average, the response time of the bigger object size ($M = 1827.70$ ms, $SD = 333.22$ ms) increased by 3.24% over the response time of the smaller object size ($M = 1770.37$ ms, $SD = 304.65$ ms). The results showed the opposite effect of the hypothesis (that the response time would decrease when object size increases). The spacing between objects might have affected the results. Bigger objects (target and distractors) in the given 4x6 grid space decreased the size of the spacing between objects, thereby creating a higher density in the display.

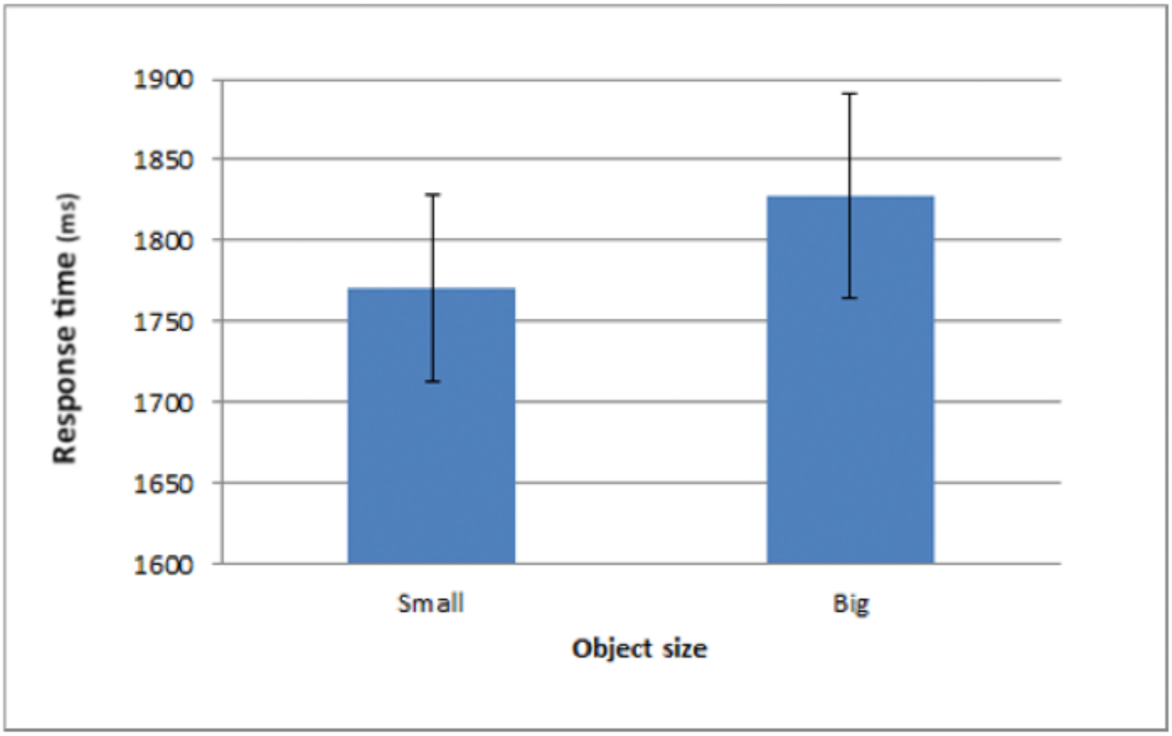


Figure10. Object size main effect on response time.

The effect of density on visual search tasks has been reported in many previous studies (Everett & Byrne, 2004; Tseng & Howes, 2008; Vlaskamp, Over, & Hooge, 2005), and the effect of density might interfere with the object-size effect in the current study.

There was no significant main effect of the contrast ratio on the response time, $F(1, 28) = 0.20$, $p > .05$.

As hypothesized, a significant main effect of the target location on the response time was found, $F(1, 28) = 47.82$, $p < .001$. On average, the response time when a target was presented in the inner area ($M = 1727.77$ ms, $SD = 300.21$ ms) decreased by 7.62% over the response time when a target was presented in the outer area (*M* = 1870.30 ms, *SD* = 340.94 ms) on a mobile device screen.

There was a significant interaction between the target location and the walking condition, *F*(1, 28) = 6.77, *p* < .05 (see Figure 11). The difference in response time between the inner area and the outer area was smaller in the walking condition than in the standing condition.

No other 2-way, 3-way, and 4-way interactions were significant.

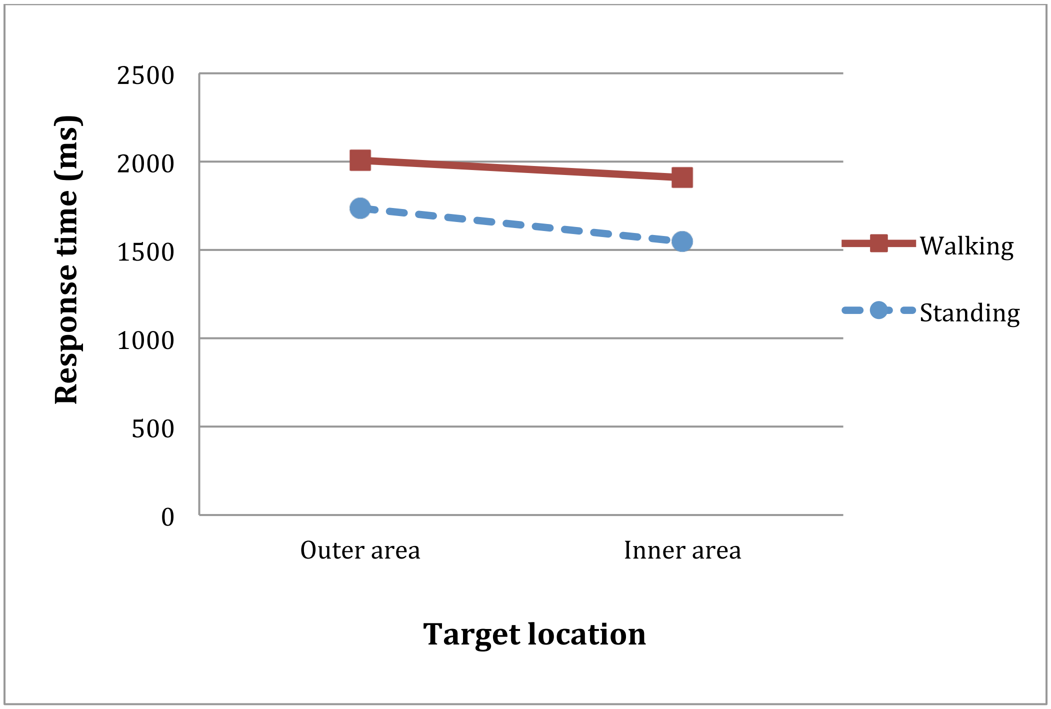


Figure 11. Interaction between walking conditions and target locations on response time.

5.2 Error Rate

The mean error rate was calculated for each participant in each of the sixteen conditions and was submitted to a 2 (walking condition) x 2 (object size) x 2 (contrast ratio) x 2 (location) analysis of variance (ANOVA). The error rate was calculated by dividing the number of trials with incorrect responses by the total number of trials in each condition.

There was a significant main effect of contrast ratio on the error rate, $F(1, 28) = 4.82$, $p < .05$. The error rate of the high contrast ratio condition ($M = 0.008$, $SD = 0.011$) was significantly higher than the error rate of the low contrast ratio condition ($M = 0.005$, *SD* = 0.005). However, both error rates were less than 1%, and the effect could be trivial. The error rate data did not produce any other significant main effects or interactions.

5.3 Walking Speed

To measure the walking speed changes between the normal walking speed and the walking speed while using a mobile device, participants were asked to walk around the track for one lap in their normal walking speed and the time for one lap was logged prior to the trials. In addition, participants were instructed to keep their normal walking speed during the trials and the walking time during the trials for 1 lap was logged. A dependent samples t-test was conducted to test for a difference between the participants' normal walking time and their walking time while performing visual search trials on a mobile device. Results showed that walking time during the visual search trials on a mobile device (*M* = 5400.345 ms, *SD* = 665.388 ms) was significantly longer than the normal walking time (*M* = 4419.035 ms, *SD* = 394.726 ms), *t*(28) = -10.405, p<.001. On average, the walking speed during the visual search trials on a mobile device took 22.21% longer than the normal walking speed.

5.4 Workload Self-assessment

Participants assessed their mental demand, physical demand, temporal demand, performance, effort, and frustration for the trials based on their subjective judgment after each block: one block for the walking condition and the other block for the standing condition. In the workload self-assessment, 5-point scales (Very low 5–4–3–2–1 Very high) were used. To compare workload self-assessment ratings between the walking condition and the standing condition, dependent samples t-tests were used.

The mental demand of the standing condition (*M* = 3.62, *SD* = 1.115) was significantly less than the walking condition (*M* = 2.90, *SD* = 1.081), *t*(28) = 4.638, *p* < .001. The physical demand of the standing condition (*M* = 4.17, *SD* = 0.966) was significantly less than the walking condition (*M* = 3.38, *SD* = 1.015), *t*(28) = 4.075, *p* < .001. The effort of the standing condition (*M* = 3.48, *SD* = 1.184) was significantly less than the walking condition (*M* = 2.83, *SD* = 1.002), *t*(28) = 3.494, *p* < .01. There was no significant difference between the temporal demand of the standing condition (*M* = 3.24, *SD* = 0.951) and the walking condition (*M* = 3.17, *SD* = 1.002), *t*(28) = 0.338, *p* > .05. Prior to the trials, participants were instructed to focus on the visual search task primarily and that might have led the participants to not rush on the trials regardless of being in the walking or standing conditions. There was no significant difference between the participants' perception of their visual search task performance between the standing condition (*M* = 4.21, *SD* = 0.774) and the walking condition (*M* = 4.07, *SD* = 0.704), *t*(28) = 0.891, *p* > .05. There was no significant difference between the frustration during the visual search tasks while standing (*M* = 4.17, *SD* = 1.037) and while walking (*M* = 3.86, *SD* = 1.156), *t*(28) = 1.470, *p* > .05. These results suggest that participants perceived that the trials in the walking condition required more mental demand, physical demand, and effort than the trials in the standing condition.

The overall workload self-assessment score was calculated by summing all 6 ratings of each participant for the walking condition and for the standing condition. The overall workload self-assessment scores of the walking and standing conditions were compared using a dependent samples t-test. Overall workload self-assessment ratings in the standing condition (*M* = 22.90, *SD* = 4.186) were significantly less than in the walking condition (*M* = 20.21, *SD* = 3.913), *t*(28) = 3.941, *p* < .001.

Chapter 6 Discussion

Although several previous studies have examined the effects of mobile user interface attributes on the target search performance while walking, the focus of the previous studies was physical target selection performance (Lin et al., 2007; Park et al., 2008; Schildbach & Rukzio, 2010). Few studies have investigated the effects of mobile user interface attributes in the perception process during mobile interface use. The current study aimed to examine the perceptual processes that facilitate visual search tasks during mobile use while excluding physical target selection aspects. The visual search process is required in many activities on the mobile user interface and involves perception and cognition steps. The current study revealed that walking, object size, and target location had significant effects on the visual search response time.

As hypothesized, walking slowed visual search, and this confirms the results of previous studies. Mizobuchi, Chignell, and Newton (2005) reported that text input while walking was slower than while standing during their mobile text entry performance research. Schildbach and Rukzio (2010) examined the effect of walking on target acquisition and text reading task performance and confirmed the negative effect of walking for both tasks. Lin et al. (2007) examined the task of tapping on predefined targets on a PDA and found that the obstacle course condition had a lower task completion time than the seated condition. In these previous studies, the physical target selection with the finger tapping on the target displayed on a mobile device was examined. The current study revealed that negative performance effects happened not only in physical tasks but also in the visual perception process during visual search on a mobile device.

The workload self-assessment rating of the current study showed that mental demand, physical demand, and effort in the walking condition were greater than in the standing condition. This is consistent with Lin et al.'s (2007) target acquisition study, which showed that the obstacle course condition had a higher perceived workload and lower perceived performance rating than the seated condition. The finding that workload is increased for a visual search while walking suggests a need for future work to design user interfaces for mobile devices that can reduce the user's mental and physical workload while walking.

In the current study, large object size was expected to lead to better visual search performance, but interestingly the large object size slowed the visual search completion. There was no significant effect of the object size on the error rate. These results contrasted with previous findings (Hasegawa et al., 2008; Lin et al., 2007; Schildbach & Rukzio, 2010). The difference in results between the current study and previous studies might be due to the inter-object spacing difference between the larger object display and the smaller object display. In the current study, unlike the previous studies, larger object size reduced the spacing between objects in the display, and the reduced spacing between objects may have made the visual search more difficult. Hasegawa et al. (2008) increased spacing between letters as the letter size increased in the display. In the study of Lin et al. (2007), the spacing effect between objects was not applicable because they displayed one target at a time.

The current result that visual search is slowed with the smaller spacing between objects along with larger object size is consistent with some previous studies on the effect of inter-object spacing. Wickens and Andre (1990) examined the inter-object spacing effect in the object display and reported the negative effect of high spatial proximity with clutter. Ling and Schaik (2006) and Lee, Chao, Ko, and Shen (2009) used letters to find the inter-object spacing effect and found that high density increased the visual search time, in agreement with the current study's results. However, Everett and Byrne (2004) and Tseng and Howes (2008) used icons and image thumbnails to find the inter-object spacing effect and found that a higher density decreased the visual search time. The range of inter-object spacing also might cause the result conflict. Vlaskamp et al. (2005) found that the inter-object spacing effect varied over different inter-object spacing ranges. Decreasing inter-object spacing decreased the search time in the inter-object spacing range from 7.1° to 3.4°. There was no inter-object spacing effect in the inter-object spacing range from 3.2° to 1.5°. Decreasing inter-object spacing increased the search time for inter-object spacing smaller than 1.5°. In the current study as well as the studies of Ling and Schaik (2006) and Lee et al. (2009), a smaller inter-object spacing range might have been used unlike the studies of Everett and Byrne (2004) and Tseng and Howes (2008). This supports the idea of inter-object spacing involvement in the unexpected results of the object size effect investigation in the current study. This also suggests a need for further investigation on the inter-object spacing effect in a mobile display.

In the current study, there was no difference in response times between the low contrast ratio (2.85:1) and the high contrast ratio (21.00:1), similar to the results of the previous studies. Schaik and Ling (2001) studied the effects of background contrast on visual search performance in web pages, and they did not find the effect of contrast on either accuracy or speed. Similarly, Hasegawa et al. (2008) evaluated the legibility of characters on a mobile phone display and did not find the effects of the contrast ratio on the letter search time. Zuffi, Brambilla, Beretta, and Scala (2007) studied the effects of contrast on readability, and they recommended at least 3:1 as a minimum contrast ratio for good visual performance. The World Wide Web Consortium (W3C) also recommended 3:1 contrast ratio as a minimum contrast ratio in large-scale texts (at least 18 point [6.77 mm] regular or 14 point [5.26mm] bold). In the current study, the low contrast ratio (2.85:1) used was very close to the industry minimum contrast ratio recommendation (3:1 for large scale texts) and the object sizes used were close to the size of large-scale texts. That might have led to the non-significant effect of the contrast ratio on the visual search performance. The current results suggest that the contrast ratio has little effect on a visual search on a mobile device at least for contrasts that are near or above the W3C suggested ratios.

The results showed that the visual search was completed more quickly when the target was in the inner area of the mobile device screen than when it was in the outer area. This was expected because the distance between the target location on the previous trial and on the current trial is likely to be less for a target in the inner area than for a target in the outer area. The current study supported this prediction. Park et al. (2008) examined the location effect on a physical target selection task performance on a mobile device and found improved performance near the center of the display. Unlike Park et al.'s (2008) study, the current study isolated the effects of the target location on the visual perception and visual attention processes. To control the physical aspect of the target selection, selection buttons were separated from the target display area. The current study showed that the target location affects not only physical target selection but also visual perception and attention during mobile use. This result has important implications for mobile device user interface design. It suggests that placing targets such as contents to read, or call-to-action buttons, in the inner area of the display is likely to facilitate perceptual and cognitive task performance on a mobile device.

Chapter 7 Conclusion

Along with the exponential increase of smartphone and tablet use, mobile device usage while walking has increased followed by the increase of safety concerns. Many previous studies have reported a negative performance effect of walking during physical target selection tasks on a mobile device. Unlike the previous studies, the current study aimed to examine the visual perception and attention processes during visual search tasks on a mobile device by controlling for physical target selection aspects.

In current research, the results confirmed the negative performance effect of walking and found the effects of the object size and the target location during visual search tasks. Small (6.74mm) object size resulted in faster response time than larger (9.5mm) object size. When the target appeared in the inner area of the mobile device, the visual search was faster than when it appeared in the outer area of the mobile device screen. This suggests that placing major content and call-to-action items in the inner area of the display would likely facilitate task performance on a mobile device.

Chapter 8 Future Work

The effect of the target location found in the current study merits further investigation. In future studies, the optimal location and the treatment of specific mobile user interface elements, like alerts and call-to-action buttons, should be examined in an ecological approach. For example, the effect of target location on task performance on mobile user interfaces can be examined by comparing the placement of alerts in different locations (see Figure 12) on a mobile device.

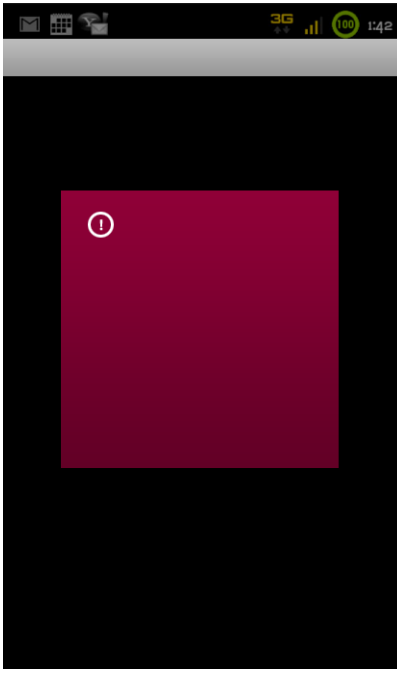
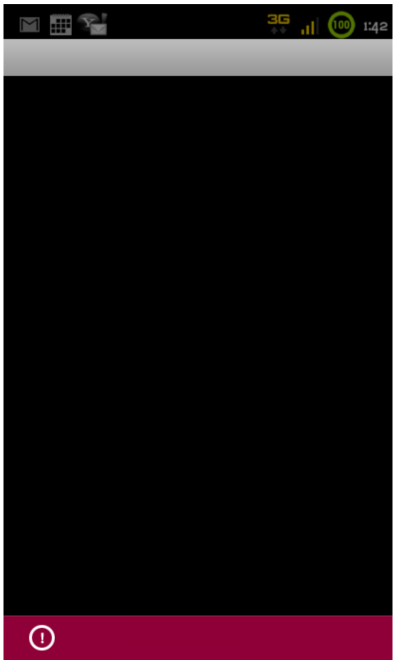
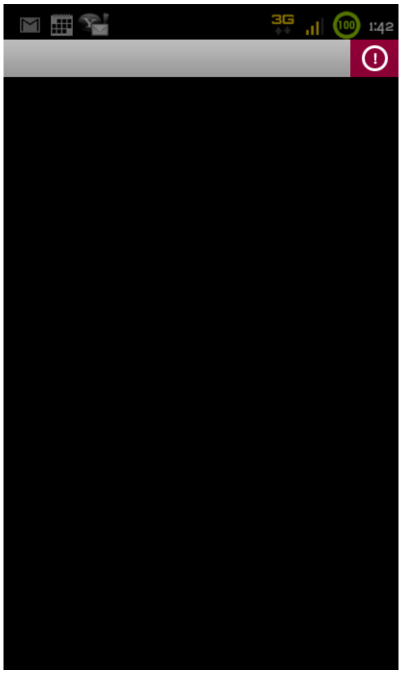
	
Option 1: Alert on popup	Option 2: Alert banner on top
	
Option 3: Alert banner at the bottom	Option 4: Alert icon on top bar

Figure 12. Possible alert locations on a mobile device.

In addition, the unexpected object size effect (smaller size reduced response time) found in the current study needs more clarification. The effects of object density and inter-object spacing during a visual search on a mobile device should also be investigated further.

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Appendix A: Post-Block Questionnaire

- Workload self-assessment questionnaire (see Figure 8)

- Self-assessment questionnaire and self-report

Walking speed How fast were you compared to your normal walking speed?	Very fast 5 – 4 – 3 – 2 – 1 Very slow
Easiness How easy was the visual performance test?	Very easy 5 – 4 – 3 – 2 – 1 Very difficult
Hand usage during the experiment Which hand did you use to hold the phone?	☐ Right-handed | ☐ Left-handed

Appendix B: Post-Experiment Questionnaire

- Daily personal phone usage

Personal mobile phone type	☐ Smartphone | ☐ Feature phone (non-smartphone) | ☐ None
Hand usage	☐ Right-handed | ☐ Left-handed | ☐ Both-handed
How often do you use your phone? Check one.	☐ Less than 3 times a day | ☐ About 3~10 times a day | ☐ More than 10 times a day ☐ Other, please specify. ________________
Which functions of the phone do you most often use? Check one or more functions that apply.	☐ Phone call | ☐ Email | ☐ Text messaging | ☐ Picture taking | ☐ Video recording | ☐ Web surfing | ☐ Navigation | ☐ Other, please specify. ________________