

Assessing the effect of different input modalities on error recovery

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1 Introduction

In February 1998, a national Dutch television station aired a short clip of the country's minister-president at that time being taught how to use e-mail by an 11 year old girl. She instructs the minister-president to 'use the mouse to go to bookmarks', after which he picks up the mouse and tries to use it as a remote control. Whether or not the events were real or staged is uncertain, as it could have been a simple joke in a kids program. In either case, he was not the only one having trouble using a computer mouse. There are many anecdotes about people using a computer mouse incorrectly. After reading quite a few, it seems that there are, or at least were when the computer was still a new piece of technology for everyday consumers, several misconceptions with regards to the use of the mouse. These misconceptions include:

- Holding the mouse like a remote control.
- Holding the mouse against the computer screen.
- Improper orientation of the mouse, e.g. rotated 90 degrees counter clock- or clock-wise, or even 180 degree rotation.
- Lifting the mouse vertically from the desk when instructed to move the mouse up.
- Being confused by the terminology of left- and right-clicking. Users often reported they were left-handed when instructed to right-click.
- Being confused with the instruction to 'click the left mouse button', resulting in a report of owning just one mouse.

These anecdotes may be outdated, as some of them feature explicit descriptions of a mechanical ball-mouse. However, at least one featured an optical mouse, which incidentally looked better to the user with the red light on top, indicating this particular anecdote was recorded after the introduction of optical mice in 1999.

Showing these anecdotes to people who have either worked with computers since they were readily available to the everyday consumer, or for people who grew up with them, almost seems mean to the people described in them. However,

especially in the early days, encountering these misconceptions is not difficult to imagine. For example, the instruction to 'move the mouse up' results in an inexperienced user actually lifting the mouse from the table. In fact, the user is doing exactly what he is *told* to do; unfortunately, the instructor was conceptually a step ahead. The same thing is the case with users that hold the mouse and point it at the computer screen after being instructed to 'use the mouse to point towards...'. Conceptually, this is also a reasonable action considering these users might have been novel to the concept of computer mice, but experienced using television remote controls.

One piece of technology that does not suffer from such misconceptions and that is quickly making its way into consumers' lives, is the touch screen. Many people believe that the touch screen is a new development in the field of consumer electronics, which is both accurate and not. The first touch screen sensor was invented in the early 1970's (Hurst & Parks, 1972), and the main implementation of this sensor technology included ATM machines and kiosk terminals. These machines were quite large and bulky, making implementation for use by the everyday computer user virtually impossible. This does not imply that these particular machines are obsolete, the Dutch railway company NS for example, installed many ticket vending machines with touch screens over the past several years. The current level of technology has progressed to a point where the sensor technology can be scaled down to fit even mobile phones, thus creating an explosion of the amount of touch screen devices on the market. It might therefore *seem* like the technology is new, even though it has been around for quite some time. A good example of this is Apple's iPhone or the more recently released iPad, that quite successfully incorporate the touch screen technology. Following Apple's example, many more mobile phone manufacturers have implemented touch screen capability in their products as well. Additionally, there is also a number of computer monitor manufacturers who have decided to develop relatively cheap touch screen monitors for the everyday consumer. These monitors are already available, however due to cost, the everyday consumer is not likely to own one. Finally, software developers are also implementing touch screen support in their software packages, such as Microsoft's Windows

7, in anticipation of an increase in touch screen use. However, even though the price of touch capable devices are in the range of the average consumer, they are more expensive than their non-touch capable alternatives. One of the questions that you can ask yourself is why touch capable devices are this popular.

One explanation may be that users find touch screens easier to work with, often claiming it 'feels more natural'. Considering the mouse anecdotes described earlier; instead of using a mouse to direct a cursor to the intended target, one simply touches it. However, for users who are quite adept in using a computer mouse, one could argue that a difference in performance is only minimal.

Another explanation could be that touch screens are regarded as something 'only seen in science-fiction movies'. The ever popular TV-series *Star Trek: The Next Generation* features a touch capable computer interface for example. Additionally, although many science-fiction movies have since entertained the idea of holographic (touch-) interfaces (e.g. *The Matrix*, *Avatar*), other science fiction producers still opt for a more 'down-to-earth' level of technology. An example of this are the tablet pc's used in *Stargate: Atlantis*.

A third explanation could be that the driving force behind touch screen popularity is the nature of the device itself. Instead of using a mouse, which requires a proper surface to use it on and either has a cord or requires batteries to work, you simply touch the screen to select the intended target. And although a mobile phone doesn't require a mouse, other forms of input have been developed to facilitate moving in and around menus, such as jog wheels or directional buttons.

However, there is evidence that touch screen devices are not always as beneficial as one might think. If the reason for touch screen popularity is because it is a fad, the impact of the disadvantages of touch screen is of less importance than when the popularity indicates a trend towards a touch screen oriented future in technology. If the latter is the case, the disadvantages must be addressed.

This thesis takes a more in-depth look into the advantages and disadvantages of touch capable devices over their non-touch capable counterparts. Additionally, using theories on visual perception, response selection, motor

programming, error monitoring and error recovery, the cognitive mechanisms behind the advantages and disadvantages are investigated. Specifically, the experiment used was designed to discover if the touch screen holds an advantage over the computer mouse in terms of selection times, error rates and error recovery.

2 Theoretical Framework

In the case of working with a computer mouse, there are several processes working together to move a mouse cursor from its initial position, to an intended target. The user must locate the mouse cursor in order to be able to track it, the proper target must be found and selected, the mouse must be moved in order to move the mouse cursor and visual feedback must be incorporated into the movement of the mouse in order to accomplish the eventual proper target selection. When using a touch screen however, there is no mouse and no mouse cursor. This section of the thesis will first give an overview of research on the touch screen and the computer mouse. Afterwards, several aspects of human cognition that play a large role in using these input devices, will be discussed. Finally, from the cognitive theories and observations, a cognitive account of working with these input devices will be extrapolated.

2.1 Computer mouse versus touch screen

The lack of additional input devices when using a touch screen can be considered an advantage in certain situations, such as information kiosks (Potter, Weldon, & Shneiderman, 1988). Potter et al. (1988) however also indicate that widespread touch screen use is limited by high error rates and a lack of precision. Much research has since focused on determining accuracy of touch screens, and on ways to improve accuracy and precision (Forlines, Shen, & Buxton, 2005; Forlines, Shen, & Vernier, 2005; Benko, Wilson, & Baudisch, 2006; Forlines, Widgor, Shen, & Balakrishnan, 2007). The computer mouse for instance can be used, with effort, to select 1x1 pixel targets. However, touch screen research indicates that for target sizes of less than 16x16 pixels, target selection errors rise dramatically. Benko, Wilson & Baudisch (2006) found error rates of ca. 95% for

1x1 pixel targets vs. ca. 5% for 16x16 pixel targets in the touch screen condition. These results can be explained by considering the actual sizes of the targets. On the touch screen Benko et al. (2006) used, 1x1 pixel corresponded to a 0.60x0.60 mm. target, which is much smaller than the surface of the fingertip that attempts to select it. The 16x16 pixel target on the other hand corresponded to a size of nearly a centimeter (9.6mm) in both width and height, which is about the size of the surface covered by a fingertip when pressing down on something. Therefore, increasing target sizes should aid in reducing error rates using touch screens. However, even with increased target size, the overall selection error is higher with touch screens than it is when working with the mouse (Forlines, Widgor, Shen, & Balakrishnan, 2007).

Using a computer mouse, there is an additional function beyond simple point-and-click operations that cannot be used when using a touch screen, namely what Benko et al. (2006) call 'tracking'. Tracking indicates the cursor state where the user hovers over a specific element which can show additional information (Benko, Wilson, & Baudisch, 2006). An example of this is a roll-down menu on a webpage, which display certain menu items when the user uses the mouse to hover over the parent menu item, although in web design this is more commonly known as *hovering* or *mouse-over events*.

There is however a concern that must be raised when generalizing the research carried out by both Benko et al. (2006) and Forlines et al. (2007); the touch screens used in the previously discussed experiments were both relatively large, with a relatively low resolution, compared to the standards at the time of writing. For example, Benko et al. (2006) used a 30" touch screen, with a resolution of 1024x768 pixels, resulting in a pixel size of 0.60x0.60 mm (width of screen in mm/width in pixels, and height of screen in mm/height in pixels). However, one of the touch screen

monitors currently available (Acer T230H), is a 23" screen with a maximum resolution of 1920x1080 pixels, which results in a pixel size of 0.27x0.27 mm, less than half of that used by Benko et al (2006).

This is important considering the fact that most, if not all, computer screens used by the average user are smaller than 30", as large TFT screens are fairly difficult and expensive to construct. Therefore, the minimal target size discussed in literature, should actually be scaled upwards to account for increased screen resolutions of the touch screen monitors on the market. When both the screen width and height are smaller, and the resolution higher than those used by both Benko et al. (2006) and Forlines et al., the pixel size decreases. This would effectively result in a smaller target and subsequently more selection errors. One could argue that there is need for a certain degree of adaptivity in software to cope with different screens and resolutions. A relative screen/resolution independent rule of thumb would be to make the minimal target size roughly 1x1 cm in size.

There are indicators to believe that, since the previously mentioned papers were published, efforts have been made to account for the problem of targets that were too small. Recently, several manufacturers have released software that specifically target the future touch screen market. One of these products is Microsoft Windows 7, which includes touch screen support. Even without using a touch screen there are several elements in the Windows 7 interface that do seem to be larger than they need to be in order to be accurately accessible with the mouse (see Figure 2.1). It is uncertain whether this was a deliberate design decision in order to facilitate possible touch screen users, but the end result makes at least the taskbar items as well as the start menu button easily accessible for touch screen users. The importance of this lies in the fact that

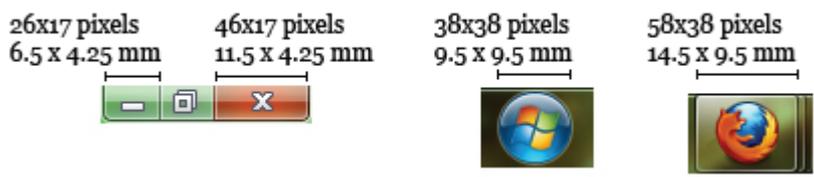


Figure 2.1. Several elements from the Windows 7 GUI that seem to be made larger in order to facilitate touch screen users. The screenshot was taken from a 22" TFT screen with a resolution of 1920x1080 pixels.

the graphical user interfaces (GUI's) are being changed already to better accommodate touch screen usage, whether these design decisions are intended as such or purely aesthetic.

Thus far, the limitations described can be, or in some instances have been, solved by adapting the software. Enlarging buttons in a GUI is something that would not have been feasible several years ago, because both the screen sizes and the resolutions were smaller, meaning less space available for large targets. The tracking problem described earlier, is also in the process of being solved. Recently, a press release was published describing a new method to 'sense' a finger hovering over the touch screen (Panaitescu, 2010).

2.1.1 Touch screen advantages

As stated in the introduction, subjective user experiences for the touch screen are often positive. Additionally, the touch screen is also implicated in quick learning and rapid performance (Potter, Weldon, & Shneiderman, 1988). Ease of use can possibly be explained by the fact that a touch screen does not require learning to use an additional input device to select a target. Furthermore, touch screens are fairly intuitive, a property not readily attributed to the mouse following the Dutch minister president example mentioned in the introduction.

A second advantage of touch screens is that they are faster when selecting a target. That is, provided the target sizes as discussed earlier are of sufficient size, selection reaction times are faster for touch screens compared to computer mice (Forlines, Widgor, Shen, & Balakrishnan, 2007). For unimanual input, i.e. a single mouse versus a single hand, the time it took to select a target differed significantly between the input devices, however only marginally. For bimanual input, i.e. two mice versus both hands using a multi touch screen, the difference in selection times was almost 5 times higher compared to the unimanual task.

For tasks such as scaling and rotating images, the multi touch screen offers a large advantage over using two separate mice. However, in for example the graphic program Adobe Photoshop, these tasks can be easily carried out using the

keyboard and a computer mouse. It is therefore unfortunate that Forlines et al. (2007) only included a two mice condition vs. a multi touch screen, and not an additional keyboard plus mouse vs. multi touch screen condition. Using the mouse with an untrained hand (which does not necessarily imply ones non-dominant hand), is more difficult, whereas most people do not have a problem with either hand when pointing towards something. Nevertheless, the research of Forlines et al. (2007) does indicate the advantage of a multi touch screen.

2.2 Cognitive strengths and limitations

In Human-Computer Interaction, as the name suggests, there is need to consider both sides of one coin. So far, the discussion only focused on the computer-side, the hard- and software strengths and limitations of the input devices. However, human cognition is not without its own limitations and strengths. This section will focus on some of these with respects to the computer mouse and touch screen.

Figure 2.2 shows a simplified schematic representation of the steps involved in target selection, separated by input device. In case of the mouse, the user must locate both the target and the mouse cursor in order to plan the movement to select the target. During the movement, visual feedback is provided with which the movement can be fine tuned. Once the target is reached, one must click to select it. After selection of the target, visual feedback can be used to assess whether or not the correct target was clicked. For example, when choosing an internet browser from a list with programs, if the wrong program shortcut is clicked, the feedback would be the wrong program that was started.

In the case of the touch screen, during the hands' movement, visual feedback *can* be used to fine tune the movement, however, only to a certain extent; the finger, hand or even the arm can obscure portions of the screen. Especially when working with small targets, even the finger can obscure the target entirely, making it more difficult to fine tune the movement based on visual feedback alone: even though you reached the target already, it is possible your finger is not exactly on target, resulting in touching a non-target area. After

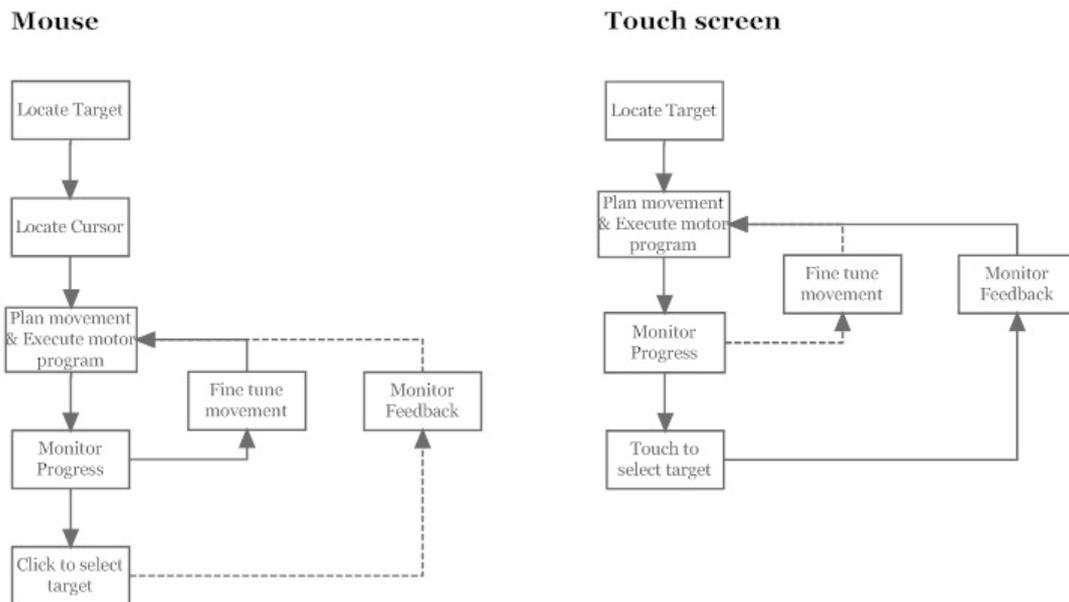


Figure 2.2. Schematic representation of the difference in cognitive processing steps between mouse and touch screen.

touching the screen, visual feedback is used to a much larger extent to confirm whether or not the correct target was selected.

The corresponding cognitive modules involved in working with either the computer mouse or a touch screen are: visual perception, response selection and motor programming, error monitoring and error recovery. The next section will give an overview of these modules, what strengths and weaknesses they have, and how they contribute to the strengths and weaknesses of the computer mouse and touch screen.

2.2.1 Visual perception

In order for a target to be responded to, it needs to be perceived. Perception of a target may be fast, however it may also be slow and effortful. Very fast visual perception concerns the perception of gist (Oliva, 2005). That is, it is possible for participants to be able to report the gist of a scene, after an image has been presented for a mere 30 ms (Koch & Tsuchiya, 2007). This very brief presentation time is too short for the participant to attend specific features of the image, yet the visual system is able to process some relevant, reportable information. Additionally, Koch and Tsuchiya (2007) describe the pop-out effect in visual search to be part of this concept as well. The pop-out effect is characterized by a specific visual target that is distinctly different from the distractors. For example a rectangle presented in an array of circles. The pop-out effect can cause

problems when working on a computer. For example, there are many features in software packages that try to capture the users attention using the pop-out effect. On web pages these features include bright flashy commercial banners and pop-up advertisements (Zhang, 2006). Other programs may employ pop-up boxes as well, for example a virus scanners' notification pop-up in the lower right quadrant of the screen (as well as many other system messages), or program may play sounds to provide feedback upon completion of a certain task, etc. These elements in user interfaces can cause the user to be easily distracted from an attentionally demanding main task he or she is trying to complete (Koch & Tsuchiya, 2007).

Perception on the other hand, may also be slow, for example in the case of the change blindness effect. In change blindness experiments, participants are usually presented with a photograph of a complex scene, after which a blank screen is presented and subsequently, a second photograph similar to the first is shown. In the second presentation, a large portion of the first photograph has changed. Such a change could be the absence of a large building, or a shadow cast by a large object (for example, see Figure 2.3). Participants of such experiments however often fail to notice the difference between the two images, even when made aware of the fact that the differences are there before the experiment starts. Change blindness can also occur when actively interacting, or watching an active interaction between people. For



Figure 2.3. Example of the change blindness effect. The left image is presented to a participant, followed by a blank screen, followed by the right image. The participant should indicate what has changed. Please note that these images are homemade and are not empirically proven to elicit the change blindness effect. They are intended to clarify what the experiment may look like.

example, Simons and Levin (1998) conducted an experiment wherein the experimenter asked a participant (although they did not know they were participating in an experiment) for directions. During the interaction between the experimenter and the participant, two people carrying a door, walked in between them, so that the participants' view of the experimenter was blocked. During this time, the experimenter switched with another experimenter, and continued the interaction with the participant. When asked whether the participant had seen any change, less than half responded positively (Simons & Levin, 1998).

When considering the evidence that concerns gist-experiments, and considering evidence concerning change blindness, it would seem that there is a contradiction. How can a participant see the gist of an image within 30 ms, but be unable or at the very least much slower in detecting a fairly large change in a scene? One explanation is that people tend to process images holistically. In research on face recognition it was shown that people process a face on a fairly global scale, without putting too much emphasis on specific features, such as a small mole or scar (Eysenck, 2009, pp. 330-332). This provides an explanation for the gist evidence, you do not need much time to process the *global* features of an image. More specific features however remain occluded, which is no surprise when talking about stimulus presentation times of 30 ms. However, in the case of change blindness, it is not the gist or global features that change, but rather a specific feature that changes, a single object in a complex scene.

In terms of computer use, the change blindness, or rather the holistic processing, can be a problem when using a mouse. As the user is required to keep track of the position of the mouse cursor, any changes to the layout of all targets on the screen may lead to incorrect selections, or an increase in selection time. Change blindness in computer use has also been shown to occur when multiple windows in a user interface are simultaneously closed (Durlach, 2004).

2.2.2 Response selection and motor programming

The previously discussed concepts of visual perception are coupled to the concepts of response selection and motor programming. The

change-blindness studies show limitations in the capability of identifying particular visual features in a scene. To report that the car in the top two images in Figure 2.3 disappears, the 'car' feature has to be processed up to a high perceptual level, in order to determine it has in fact disappeared in the second image. This selection of features is called 'selection-for-visual-perception' (Schneider & Deubel, 2002).

In contrast to selection-for-visual-perception there is also selection-for-action. Consider for example you are walking down the sidewalk and there is someone walking towards you. At some point, you may choose to make a sidestep, to make sure that both you and the other pedestrian pass each other without bumping into each other. Based on both your own position and the position of the other person on the sidewalk, you may choose to take a step to your right and continue on your way. Processed visual information about the sidewalk, your proximity to the edges and the position of the oncoming pedestrian, is used by the motor system to take a sidestep. Other work in this area focused on more simplified observations, such as grasping an object amongst other, similar objects (Goodale & Milner, 1992).

The Visual Attention Model, described by Schneider (VAM, 1995), attempts to describe these two forms of selection-for in one visual attention mechanism. The VAM is based on a total of four assumptions, the first two of which are based on two visual pathways in the brain. The visual system can be subdivided to include two pathways, ventral and dorsal (Goodale & Milner, 1992). The ventral pathway seems to play an important role in processing visual information of objects (such as, shape, size, location, colour), and is assumed to play a role in selection-for-visual-perception. The dorsal pathway on the other hand seems to play an important role in processing features such as location and size, and is assumed to play a role in selection-for-spatial-motor-action (for example grasping an object).

The third assumption postulates that the VAM has a single mechanism that controls both types of selection-for. This mechanism gives processing priority to a specific object, which is then processed up to the higher-level ventral and dorsal areas, which ensures both conscious

visual perception of the object and the generation of motor programs to interact with the object, respectively. However, it must be noted that not all visual information that is important for the eventual movement, is processed to conscious awareness. Zombie behaviors are an example of such movements (Koch & Crick, 2001). These behaviors are so named because they display limited sensory-motor behavior and immediate, rapid action. Koch & Crick (2001) describe an experiment where a participant is sitting in the dark, and looks and points at a single light. After a variable time-delay, a second light appears to which the participant must then look and point. When the participants' eyes are still in transit, the second light is moved slightly. Results of this kind of experiment shows that participants have no trouble whatsoever with correcting their movements so the eyes and finger end up right on target, however they do not actually see the movement of the light.

The final assumption of the VAM states that visual perception and spatial motor action are coupled via an attentional process, and that this process couples the programming process to the perceptual processes. In less abstract terms, the intention to attend a specific target should lead to the implementation of a motor program towards this target (Schneider & Deubel, 2002).

To understand the motor program generation, consider the underlying neural mechanism of movements, described by Georgopoulos et al. (population coding theory, Georgopoulos, Schwartz, & Kettner, 1986). The researchers used electrophysiological techniques to measure motor neuron activity in the motor cortex when rhesus monkeys initiated an arm movement to press a button after being presented with a specific cue. It was found that multiple neurons fired simultaneously, and that each individual neuron encoded a different direction. Georgopoulos et al. (1986) represented each individual neuron as a single vector, based on the direction of the movement it encodes, and based on its firing rate. The average of the individual vectors corresponded to a directional movement (Figure 2.4 (I)). Furthermore, the researchers concluded that the individual neurons did not work together to generate the movement, but rather that competition *between* these neurons resulted in the eventual movement of the arm

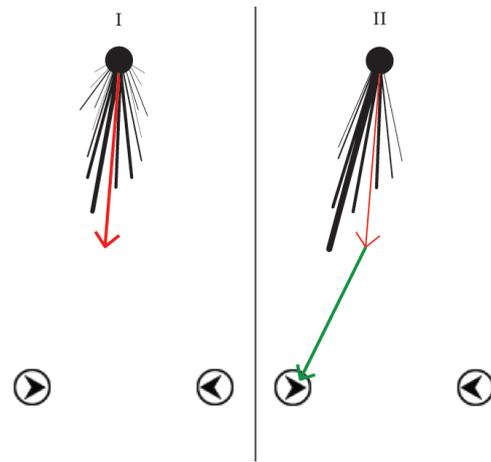


Figure 2.4. Schematic representation of Georgopoulos et al. (1986) population coding theory. I: onset of movement, neurons in the motor cortex fire in multiple directions with different weight, resulting in an average vector of movement (red arrow). II: competition between the individual neurons cause several to cease firing, whereas others gain in strength. This results in a new, refined, vector with a new direction (green arrow).

(Georgopoulos, Schwartz, & Kettner, 1986). After the onset of the movement, competition between the neurons causes some to cease firing, whereas others fire more vigorously (Figure 2.4 (II)). The new directional vector (green arrow) resulting from this population of firing neurons encodes a new, more refined, movement. It was later shown that not only neurons in the motor cortex behave in this manner, but that this is also the case for neurons in the superior colliculus (SC) in eye movements (Lee, Rohrer, & Sparks, 1988).

As the VAM indicates there is a coupling between visual processing and motor programming, evidence for which can be found in studies into the effects of distractor targets on movement trajectories. More specifically, the effects of distractor targets on motor control can be used to make inferences about for example conflicts between motor actions, called response conflicts. In order to illustrate how distractors exert their effect on motor control, consider a study involving eye movements (Van der Stigchel, Meeter, & Theeuwes, 2006). In the study of eye movements, there is a specific rapid movement of an eye from point A to B, called a saccade. An optimal saccade is one where the total travel time of the eyes between point A and B is minimized, i.e. a straight line between the start position and

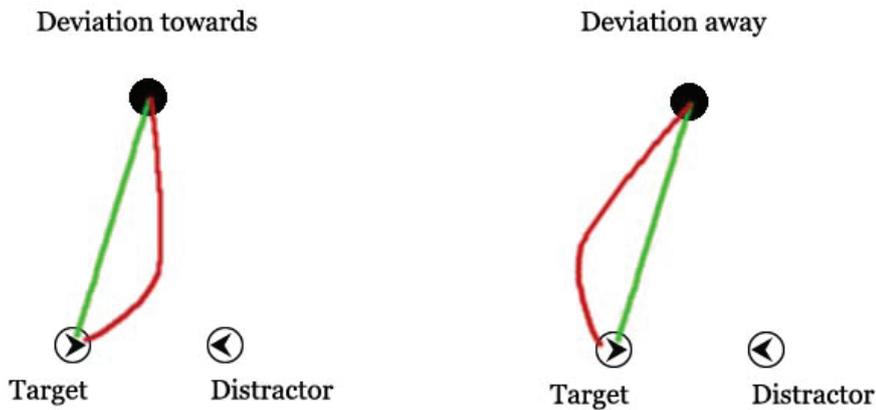


Figure 2.5. The difference between deviation towards and deviation away. The green line indicates the optimal saccade path, whereas the red line indicates the actual path.

the end position of the saccade. A deviation from this optimal trajectory indicates that, during the generation of the motor program, the visual processing system has not yet processed enough information needed to generate the optimal saccade. In the study by Van der Stigchel et al. (2006), two different deviations are described, namely *deviation towards* and *deviation away*. This terminology states that an eye-movement can either deviate towards (Figure 2.5, left) a distractor object, or away from it (Figure 2.5, right).

Van der Stigchel et al. (2006) describe three paradigms in which these deviations are shown: 1) double step, 2) global effect and 3) visual search. In the double step paradigm, the participant is presented with a target, towards which a saccade must be made. However, after a variable delay, the first target disappears and a second one appears. The participant must then make a saccade towards the second target. If the first target disappears before the first saccade has reached the target, the trajectory changes direction mid-flight towards the second target. In case of the global effect, both a target and a distractor are presented. If the space between the target and the distractor is small enough, the trajectory deviates towards, as shown in Figure 2.4 (left). In the visual search paradigm, there are more than two stimuli and deviations occur, provided: a) the distractors are not placed in a single line between the start position and the target and b) there is at least one salient distractor.

Van der Stigchel et al. (2006) used the population coding theory to account for the observed eye movement deviations, primarily that deviation towards indicates a response conflict. When

a hand or eye movement is initiated, over the course of the movement, an increasing amount of visual information is processed to make a correct selection between the target and distractor objects. If, at the onset of movement, too little visual information has been processed, the population coding theory states that there is not enough inhibition to guide the movement in an unambiguous direction. This results in a movement that is directed towards an intermediary position between the objects. As more visual information is processed, the movement is refined, resulting eventually in a correct selection of the proper target object. The movement towards an intermediary position occurs assuming, as the VAM postulates, a movement is initiated before the target object has been processed to the higher level areas of the visual cortex. For example, when a ballistic movement is made towards an estimated location of the intended target, e.g. an array of stimuli where the target will be displayed but where the exact location of the target is not disclosed. The ballistic movement in this case shows ‘reach dynamics’, i.e. relatively low acceleration and deceleration, such as pointing. Ballistic movements with reach dynamics should not be confused with those involving high acceleration and deceleration, which are said to have ‘strike dynamics’, such as hitting. In addition, with reach dynamics concerning a relatively small object, such as a small target on a touch screen, the deceleration is typically set in earlier in the movement, and the deceleration phase is also prolonged to allow for fine tuning (Vitaladevuni, Kellokumpu, & Davis, 2008).

The interpretation of deviations away, in the case of eye-movements, is less clear. It has been hypothesized that deviations away are the result of top-down influence, for example in experiments

where the participant is explicitly instructed not to make an eye-movement towards the distractor object. This can be interpreted as a rather abstract experimental setup, however, it is interesting to see that the instruction not to look creates an overshoot of necessary inhibition towards the distractor. Van der Stigchel et al. (2006) describe two possible explanations for this: 1) the resulting inhibition from neuronal competition allows for a larger-than-needed shift in the directional vector and 2) trying to not look at the distractor may activate too much neurons that encode movement towards and to the non-distractor side of the target object, leading to a overcompensated movement which is later refined.

Aside from the evidence presented by Van der Stigchel et al. (2006) on the deviations of eye movements, similar deviations away were obtained in hand movement studies. A less abstract example of deviations away was offered by Howard & Tipper (1997). When participants attempt to reach for and grasp an object, amongst a set of objects, the trajectory of the hand deviated away from non-target objects. It has been suggested that the participant employs some form of control in order to avoid colliding with the distractor objects (Chang & Abrams, 2004). Chang & Abrams replicated the earlier observed deviations away, using physical objects. However, when they replaced the physical distractor objects with virtual distractor objects, they observed a deviation towards these distractors.

Deviations towards distractor objects have also been reported in other studies concerning hand movements (Tipper, Howard, & Jackson, 1997; Tipper, Lortie, & Baylis, 1992). It was shown that hand movements deviate towards distractors, provided the distractor was located somewhere in the space between the hands' initial starting position and the location of the target (Tipper, Lortie, & Baylis, 1992).

Finally, deviations towards distractors have also been observed in computer mouse movements. For example, an experiment on ambiguous language comprehension, showed that ambiguous sentences could influence mouse movement towards an incorrect ambiguous target (Farmer, Cargill, Hindy, Dale, & Spivey, 2007). In another study (Welsh, Elliott, & Weeks, 1999), participants were required to select a specific target amongst

an array of stimuli, by moving the computer mouse as quickly and as efficient as possible from the 'home' position (indicated in the interface). Although the presence of the distractor did not influence reaction time, or movement time, it did introduce deviations toward (Welsh, Elliott, & Weeks, 1999).

In conclusion, it would seem that eye, hand and computer mouse movements follow the same general principles when trajectories are concerned. Deviation towards is indicative of a conflict between responses. Deviation away on the other hand may be indicative of top-down preparation, such as the instruction to ignore a distractor. However as Welsh et al. (1999) suggested, in the case of hand movements with a projection of stimuli (e.g. a touch screen), participants may also deviate away to avoid obscuring the stimulus with their hand.

2.2.3 Error monitoring and error recovery

Consider once more the example of walking on the sidewalk when someone is walking towards you. Sometimes, the oncoming person decides, just like you, to make a sidestep as well and often this does not pose any problems. However occasionally, the other person mirrors the sidestep you took, which results in you both still walking directly towards each other. When you realize this, you must once more assess the situation, and make sure you take another sidestep to avoid collision. In this case, you are monitoring the situation for possible errors, and when an error occurs, action must be taken to avoid or undo the resulting problem. Something similar could also happen when for example navigating a web page. Clicking the wrong hyperlink when you are trying to find a particular piece of information, leads you to the wrong page. In order to recover from the error however, you must first recognize the error to begin with.

There is a large body of evidence describing how and why humans make mistakes. This literature mostly concerns human error, and focuses primarily on examples from errors that have had profound impact (Rauterberg, 1996; Besnard, Greathead, & Baxter, 2004). Studies of this nature often focus on a single case, such as the Chernobyl disaster and the Kegworth plane crash.

Behavioral studies for less high-impact settings are less numerous on the other hand. In human error research, error handling is often considered to the point of preventing the error in the first place (Brodbeck, Zapf, Prümper, & Frese, 1993). To illustrate the importance of research into error handling, Brodbeck et al. considered error handling in normal office settings. They showed that the participants in this experiment spent 10% of their time handling errors. Additionally, of all errors made, 3.6% were not successfully corrected.

Another study (Rabbitt, 2002) showed that participants are relatively proficient at identification and correction of their own mistakes. The detection of an error is relatively slow, however error correction can be very fast. Evidence for fast error recovery is based on data obtained from participants, who were given a reaction time task where they could correct their own mistakes. The participants could correct their mistakes in as little as 20-40 ms. (Rabbitt, 2002). Rabbitt hypothesized that the fast error recovery was due to a continuous flow of perceptual information. Additionally, there also seems to be a automatic component in error correction, as participants were sometimes unable to consciously withhold themselves from correction an error when instructed not to correct mistakes (Rabbitt, 2002). The hypothesis that error correction is based on a continuous flow of perceptual information was confirmed by Yeung, Botvinick, & Cohen (2004).

In recent years behavioral studies on error monitoring, like the one by Rabbitt (2002), have been supplemented by neuroimaging data. One concept that is implicated in the human error monitoring system that has received a lot of attention, is the ERN (Error-Related Negativity). The ERN is a component of event-related potentials (ERPs) found in EEG (Electro Encephalogram) data. Specifically, the ERN is seen when a participant makes a mistake, even without conscious awareness of making the error (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001). When the mistake is made, the ERN is generated and it peaks around 100 ms. after the onset of the mistake.

The ERN has also been subdivided into response ERN (Dehaene, Posner, & Tucker, 1994) and

feedback ERN. The response ERN is observed after initiating the erroneous action, whereas the feedback ERN is observed after receiving feedback (Holroyd, Yeung, Coles, & Cohen, 2005). Additionally, it was also shown that the ERN is indicative of the severity of the error produced, that is the amplitude of the ERN becomes larger when more emphasis is put on the importance of producing a correct response (Gehring, Goss, Coles, Meyer, & Donchin, 1993).

As stated, the ERN is indicative of an error *monitoring* system, conform to the model described by Rabbitt (2002). However, there is uncertainty about what component of the monitoring system it reflects. It has been argued that the ERN reflects the error-detection process (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001), an error signal in the system that attempts to correct the error (Holroyd & Coles, 2002), or an emotional response to making the error (Gehring & Willoughby, 2002).

Using other neuroimaging techniques, further attempts were made to identify the neural structures responsible for ERN generation. fMRI research showed the neural structure responsible is the Anterior Cingulate Cortex (van Veen & Carter, 2002). The anterior cingulate cortex (ACC) is implicated in pain perception, empathy and emotion (Carlson, p. 242), in decision making and reward (Bear, Connors, & Paradiso, pp. 600-604), and is a neural site where motor intentions are translated into movements (Holroyd & Coles, 2002).

Interestingly the ACC does not only show activity when the participant makes a mistake, but is also activated when correct responses are made. This activity was associated with trials where there were response conflicts (Yeung, Botvinick, & Cohen, 2004). Further inspection of the role of the ACC in ERN generation showed that the caudal ACC showed activation on both correct and incorrect trials. The rostral part of the ACC however, only showed activity in error trials. Yeung et al. (2004) stated the hypothesis that rostral ACC activation indicates further, affective, processing of an error (Yeung, Botvinick, & Cohen, 2004). This hypothesis was further strengthened by the results found by van Veen & Carter (2002).

In recent years, the observations from ERN data have also been linked to other areas of research,

such as specific brain disorders. It was found that patients suffering from internalizing disorders, such as anxiety and depression, show larger ERN amplitudes when making an error. With externalizing disorders, such as impulsivity found with substance abusers, the ERN amplitude decreases (Olvet & Hajcak, 2008). Additionally, ERN generation has also been linked in social cognition, specifically showing race bias (Bartholow, 2010) and it was shown that higher ERN amplitude correlates with better academic performance (Hirsch & Inzlicht, 2010).

2.3 Extrapolating the theories

The theories and experimental data described thus far are valid for both touch screen and computer mouse usage and human cognition. These concepts all work together to facilitate computer use.

When using a mouse, the user needs to know where the mouse cursor is located. If you do not know where it is, you will need to find it first, otherwise there is no possible way to initiate the proper motor program to guide the cursor to the target. After locating the mouse cursor, the target must be found as well and a motor program can be set in action.

When using a touch screen, there is no mouse cursor to locate, and therefore only the target must be found. This would imply that, the touch screen is faster because of the lack of a mouse cursor to locate and manipulate. The increase in selection speed can also be an explanation for the increase in selection errors typically seen when using a touch screen, even when the target sizes are appropriately large to not bias these errors. As described, visual information is processed continually and more time spent on visual processing means more information is available to select the proper target. However, because there is no need to locate the mouse cursor, I believe that less time is actually spent on visual processing. This could mean that selection errors are typically made based on incomplete visual information.

Using the touch screen, the lack of visual information from the mouse cursor can also introduce problems selecting small targets. You do have visual information from your hand and

fingers, to indicate that you are at least close to the target. However, the fingers and hand could obscure part of the screen where additional information may be present that could help with confirming the selection. This does not imply that users do not lift up their finger from the screen, but it can be argued that they do not lift it up far enough to see the entire screen.

I wish to put forth the first two hypotheses, based on the literature describing differences in selection times and the amount of errors made between input devices (Benko, Wilson, & Baudisch, 2006; Forlines, Widgor, Shen, & Balakrishnan, 2007) and the literature describing visual processing, motor programming and response selection. These hypotheses are:

- 1) The lack of a mouse cursor removes one processing step from the workflow and cause the user to work faster with a touch screen.
- 2) The use of a touch screen increases the amount of errors made because less visual processing is available to resolve response conflicts.

Providing evidence supporting these hypotheses will shed more light on the differences between touch screen and mouse usage, as well as provide more experimental data on reaction times and amount of selection errors. Most literature that discusses the differences either use relatively old input devices, or focus primarily on other manipulations. However, very little literature provides data that purely looks at the differences between input modalities on only reaction times and the amount of errors made.

When a mistake is made, this introduces a problem, which can be minor and at worst be annoying to the user, or have major consequences. A minor problem would be the hyperlink example discussed earlier, if you select the wrong link, a new page loads which contains the wrong information. This takes somewhere between a few hundred milliseconds and a few seconds for most web pages and internet connections. After realizing the mistake, you must then go back to the previous page and try again. A major problem may arise in settings where any gain in time is preferable, but the cost of making an error is disproportionately large. The implications for touch screen implementation in these settings is larger. For example, it is preferable for the

dispatch of an ambulance to be fast, however if the wrong ambulance is sent out, correcting this mistake takes an unacceptable amount of time.

In this thesis, the focus lies on simple tasks, where a mistake is recognized most of the time and resolved relatively fast, as described by Rabbitt (2002). Assuming the touch screen is faster when selecting targets, it is possible the touch screen is also faster when recovering from the error. The question then becomes: how much faster is error recovery when using a touch screen, and can this difference negate the increase in errors made? After all, if you are much faster in recovering from the error, does it then still matter that you make more of them? Thus far however, there have been no studies that looked specifically at the differences in error recovery between the touch screen and the computer mouse. Based on the assumptions that the touch screen is faster when selecting targets and that there is a processing step missing from the workflow, the third hypothesis of this thesis is:

3) The touch screen allows for faster error recovery compared to the computer mouse.

To summarize, to investigate what differences there are between the touch screen and the computer mouse, and how *much* of an impact these differences have, the following hypotheses were formulated:

1) The lack of a mouse cursor removes one processing step from the workflow and cause the user to work faster with a touch screen.

2) The use of a touch screen increases the amount of errors made because less visual processing is available to resolve response conflicts.

3) The touch screen allows for faster error recovery compared to the computer mouse.

3 Experimental Design

In order to provide evidence for the hypotheses described, I designed an experiment that was ran both online and at the University of Groningen (main experiment). The online experiment was intended to be a pilot experiment to first obtain a large amount of mouse data from a heterogeneous population. It was assumed that it was unlikely

that the online participants possessed a touch screen monitor, and therefore no touch screen condition was included in the online experiment.

It was also assumed that because of a lack of experience with touch screen monitors, data from the participants in the *main* experiment would be a good indicator for novel touch screen users, provided the mouse data was similar to the data observed from the heterogeneous online participants. The main experiment was primarily set up to obtain data on the differences in error recovery, as well as confirm the online mouse data. The design of the experiment was largely identical for both the online pilot study and the main experiment.

3.1 Participants

3.1.1 Online Pilot

The participants of the online experiment (n=86, 64 female) had an average age of 31.5 years (SE = 9.29 years). These participants were recruited by posting the link to the experiment, along with a short post on what the data would be used for, on the internet. The locations were: a forum for digital photography, a social networking website and a forum for Dutch cat-enthusiasts. These locations were chosen based on prior experience using these forums as a site to recruit

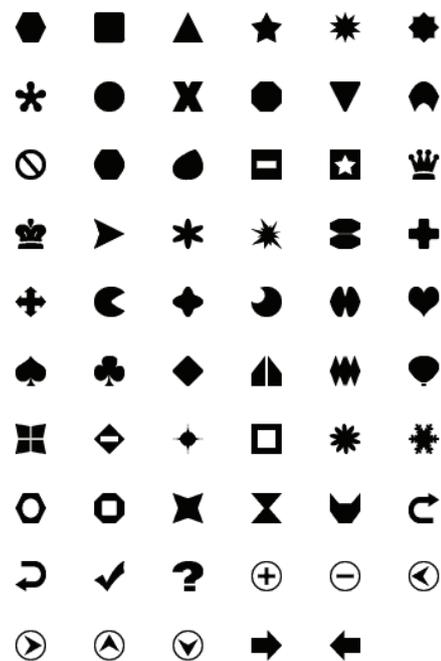


Figure 3.1. List of all the shapes used in the experiment.



Figure 3.2. The setting in which the main experiment was carried out. The touch screen was mounted on a wooden structure, under an angle of approximately 32 degrees.



Figure 3.3. Screenshots of the experiment in level 1. Top left: start of a trial, the Next-button must first be clicked. Top right: the probe (left shape), target and distractor shapes, shown after the trial was started by clicking the Next-button. Bottom left: the screen just after clicking the right target, the probe, target and distractor shapes disappear and the Next-button is once more highlighted. Bottom right: Incorrect selection causes a large red X to appear over the incorrect target and the Undo-button is highlighted. Note that the Undo-button *must* be clicked in order to continue with the trial.

participants, as well as the intended heterogeneity of the participants. Because the resolution of the experiment was too large for small screen resolutions, participants with a screen resolution of 800x600 or lower were excluded from the experiment, by code that checked this features. The participants' internet connection speed could not be as easily checked but this posed no problem, since the experiment is loaded in its entirety before the experiment starts.

3.1.2 Main Experiment

The participants of the main experiment (n=12, 7 female) had an average age of 23.75 years (SE = 3.17 years). The participants were recruited by distributing flyers amongst the students. The experiment lasted approximately 15 minutes and participants received €2,- for participation.

3.2 Stimuli

The experiment was designed and programmed using Adobe Flash CS4 and ActionScript 3 respectively. The website on which the experiment was hosted was designed using PHP, MySQL, HTML and CSS. Both the online pilot study and the main experiment were accessed via this website. The stimuli used (shown in Figure 3.1) were made using the custom shape tool in Adobe Photoshop CS4. The custom shapes were downloaded from several websites hosting so called 'packs'. The packs, and the shapes contained therein, were all licensed under the GNU general public license, meaning that no copyright laws were violated in using the shapes for this experiment. The choice of the shapes rested on two criteria:

1) The shapes should be relatively simple or well-known symbols, therefore no complex shapes were chosen. Complex characters that were considered for a 'hard' version of the experiment included for example Japanese characters. It was assumed that the knight and queen chess symbols are relatively well-known.

2) Some of the shapes should be similar to others, i.e. the arrow-shapes that are rotated 90°, 180° and 270°.

In the pilot experiment, because of the fact the participants were recruited online, little can be said about the setting in which the experiment was done.

The main experiment was run on a dual core computer, using a standard infrared 3-button mouse (HP). The touch screen was an Iiyama AS4635U (18.1"), running at a resolution of 1280x1024 pixels. Furthermore, the touch screen was mounted on an inclined structure, under an angle of approximately 32°, to avoid participants' arm fatigue, which in its original vertical position was substantial (see Figure 3.2). Before each run of the experiment, the touch screen was re-aligned. Although there was no indication of a faulty alignment after each individual experiment, this ensured that no misalignment slipped in over the course of multiple runs of the experiment.

3.3 Design and procedure

In the online pilot, the participants were first presented with a questionnaire, which they were instructed to fill out. After the questionnaire was submitted, the Flash movie was loaded and the instructions for the experiment were displayed. After reading the instructions, the participant was presented with the next screen, on which a demonstrational movie was displayed, that showed the flow of the experiment. After the demonstrational movie, the experiment was started.

Participants in the main experiment were seated in front of the touch screen in a well-lit room. They were presented with an informed consent form informing them of the intention of the experiment, and the participants' right to withdraw from the experiment if they wished to do so. After signing the form, instructions on the general flow of the experiment were given verbally and the importance of speed was emphasized. Following the verbal instructions, the website containing the questionnaire was displayed. The rest of the instructions given to the participant were equal to the ones the online participants received.

The experiment was made to resemble a simple web-based game, in order to attract online participants. The experiment was the same for both the online pilot and the main experiment, with the exception the touch screen condition was added to the main experiment. Half of the participants in the main experiment were first presented with the mouse condition of the experiment, and half were first presented with the touch screen condition. The experiment

did not include practice trials because of the demonstrational movie indicating the flow of a trial and the relative ease of the first block of the experiment.

The general overview of the experiment is as follows: Participants were presented with a shape that would remain on screen until the proper selection was made (henceforth: probe). The probe appeared on the left side of the screen, whereas an array containing the target shape and one or more distractors was presented on the right hand side (see Figure 3.3, Top right).

To start a trial, the participant had to first click or touch the 'Next'-button. This was implemented in order to generalize the data obtained from the experiment to other simple, repetitive tasks. Examples of such tasks could be internet browsing, opening and closing programs and other search and click tasks. Once the 'Next'-button was pressed, it was grayed out (see Figure 3.3, Top right) and deactivated, and the targets were displayed. The graying out and highlighting of the buttons was primarily implemented to facilitate the participants in the online pilot study. These participants had to rely solely on written instructions and a small demonstrational movie, without having the option to ask the experimenter for help. After a correct selection was made, the target and distractors disappeared and the 'Next'-button was highlighted and activated again, indicating it could be pressed (see Figure 3.3, Bottom left).

When a participant made an incorrect selection, a large red 'X' was displayed over this target, indicating the incorrect response. Additionally, an 'Undo'-button was highlighted and activated (see Figure 3.3, Bottom right). All other possible buttons, i.e. the target and other distractors, were deactivated, but not grayed out, at this point. In order to continue, the participant had to click the 'Undo'-button, after which this was once more grayed out and deactivated and the large red 'X' indicating the improper response was removed as well. Additionally, the target and distractors became active again, allowing the participant to select the proper target. The 'Undo'-button was implemented to mimic an undo button in existing programs, such as the back button in an internet browser.

During the experiment, the participants' score was

recorded and shown above the 'Next'- and 'Undo'-buttons. The score was calculated as a function of reaction time. That is, the faster the participant clicked the correct target, the more points he or she was awarded. This was implemented to encourage participants to be as fast as possible. Points were not deducted after making a wrong response, however, as the amount was based on the total reaction time of that trial (incorrect RT + Undo-button RT + correction RT), the amount awarded was lower than when a fast, correct response was made.

Additionally, the score in the online pilot could, after completion of the experiment, be uploaded to a high score board. This was implemented to encourage other users on the forums to compete against their fellow forum members. In the main experiment, the score was shown during the trials, but it was not saved on a list of high scores.

The experiment had four blocks of increasing difficulty. In the first block, there were two stimuli (see Figure 3.3), in the second block there were four stimuli, in the third block there were eight stimuli and in the fourth block there were twelve stimuli (see Figure 3.4). The increase in possible target locations implemented different task difficulty levels. The increase was also intended to make the experiment more challenging to play, since the online pilot study rested solely on the participants' motivation to continue participating. Each block in the online pilot consisted of 30 trials, whereas each block in the main experiment consisted of 50 trials. The amount of trials per block in the online pilot was deliberately kept low in order to make sure participants did not drop out because the experiment was too long.

The times of the start of a trial after pressing the next button, and at the end of the trial after pressing the correct target were used to calculate the reaction times. Additionally, reaction times were calculated between the start of a trial and the selection of an incorrect target, between the incorrect selection and pressing the 'Undo'-button, and between pressing the 'Undo'-button and the correct target. Reaction times were not calculated between trials, and mouse cursor position between trials were not logged either; primarily to reduce the amount of data obtained. Because the experiment was first hosted online, efforts were made to reduce the amount of

Table 3.1 Questions and possible answers used in the questionnaire		
Questions	Possible answers	Which experiment
Age	<12, 12-18, 19-25, 26-32, 33-39, 40-46, 47-53, 54-60, 60-65, 65+	Both
What is your gender?	male, female	Both
How many hours do you spend behind your computer on average every day:	<1, 1-3, 3-5, 5-7, >7	Both
What is it you do behind your computer (multiple answers possible):	Wordprocessing, Browsing the internet, Playing games, Using chatprograms, Programming, Graphic Design	Both
Do you have experience with touch screen devices? (Such as, mobile phone with touch screen, tablet pc, touch screen monitor)	yes, no	Both
Do you own one or more touch screen devices? (Such as, mobile phone with touch screen, tablet pc, touch screen monitor)	yes, no	Both
If you own one or more touch screen devices, please select which one(s):	Mobile phone with touch screen, Tablet pc, Touch screen monitor	Both
Are you doing this experiment on a desktop computer or a laptop?	desktop, laptop	Online pilot only
If you selected laptop in the question above, do you use a separate mouse or the touchpad?	NA, mouse, touchpad	Online pilot only

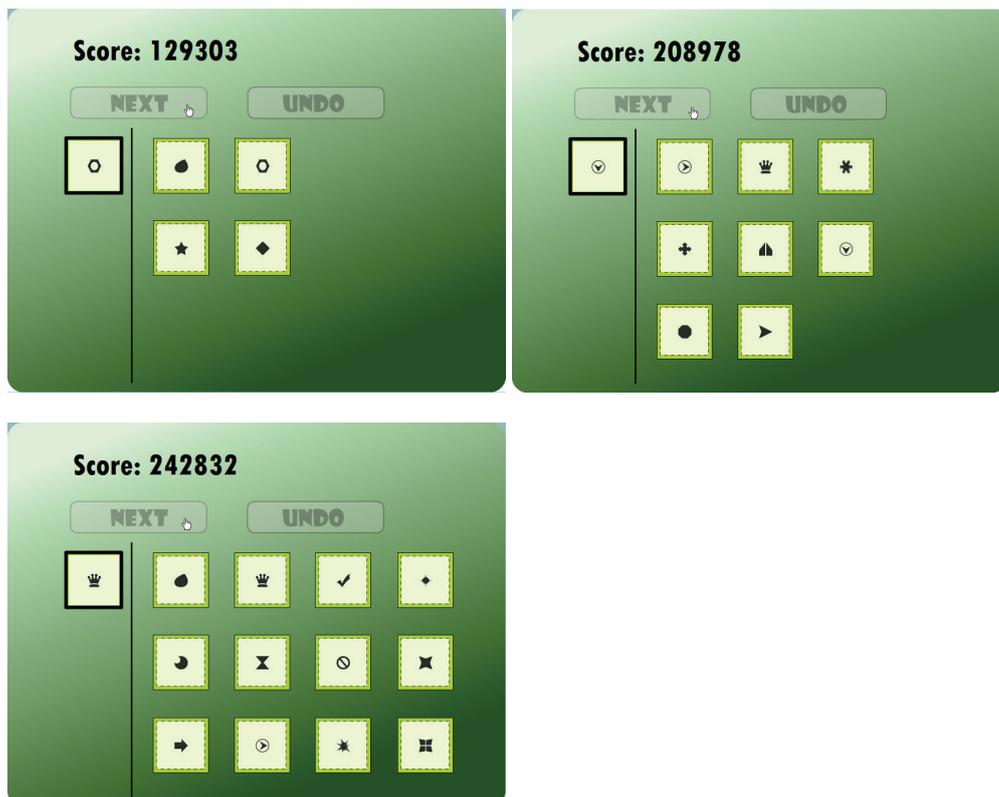


Figure 3.4. Top left: second block, Top right: third block, Bottom left: fourth block.

computations made by the server, and to reduce the size of the flash movie in order to make it run smoothly on a range of computers and internet connection speeds.

After a number of participants had completed the experiment, an additional module was programmed into the experiment. This module logged: 1) the cursors' x,y-positions when clicking a target, a distractor, the next- and the undo-buttons at the same time the reaction times were logged and 2) the x,y-positions when the mouse cursor was in transit. This module was intended to be included from the start of the online pilot study, however as stated, to reduce the server load, it was first left out to see how the experiment would fare. When running the online experiment, it was possible to get one participant per day, or one per second. In case of the touch screen section of the main experiment, no transit data could be collected, since all participants took their hand from the screen while moving from button to target. As this is a normal way of using a touch screen monitor, participants were not instructed to keep their finger on the screen, as this could influence the reaction time data. Additionally, if the participant would have been required to keep his or her hand on the screen, a large portion of the screen would have been blocked by the hand, further influencing reaction times.

3.4 Data analysis

The data analysis was virtually equal for both the online pilot study data and the data obtained from the main experiment. This section will describe the method of analysis for both experiments.

3.4.1 Questionnaire

The answers given on the questionnaire (see Table 3.1) were extracted and formatted to be imported into SPSS per individual participant. For the online pilot study, participants were discarded when it was likely the questionnaire was not filled out truthfully, or it could indicate a recurring player who had already filled out the questionnaire. This was apparent for the questionnaires where all the questions were answered with the default values. Additionally, the default age-group was set to younger than

12 years old. As this data would require consent given by the parents or guardians, these were also discarded based on that reason. The data from the second age group, 12-18 years, was discarded for this reason as well. Additionally, data from incomplete experiments was discarded as well.

In case of the main experiment, two questions were removed, namely those concerning which computer the participant was using (either desktop or laptop computer) and what input device was used when using a laptop computer (either touch pad or mouse). No participants from the main experiment were excluded from analysis based on the questionnaires, nor based on reaction times. Furthermore, no notable incidents or distractions were observed during the main experiments.

One advantage of the online pilot experiment, that was not intended in the design of the experiment, was the use of a touch pad by a subset of the online participants. Participants using a laptop were asked to fill out whether they used a separate computer mouse or the laptops' touch pad, which provided data for a third input device. Inspection of the touch pad data showed interesting results, and are therefore included in the results section as well.

3.4.2 Reaction times and amount of errors

Individual reaction time averages were calculated by extracting each trials' reaction time, and averaging them per block per condition. Every first trial from each block was removed in both the online pilot as well as the main experiment because the experiment would sometimes show the possible targets in sequence, instead of all at once. This was only the case with the first trial of a block; every other trial displayed all the targets simultaneously.

In the online pilot study several participants were discarded based on reaction times from trials that measured in the minutes to hours range. Participation was entirely voluntary, and without supervision, and it is therefore possible that a participant would for example make a cup of coffee whilst playing the experiment. Obviously, these data were excluded based on the extremely high reaction times, as well as the possibility

of an unmotivated participant. Other than the extremely high reaction times observed, in both the pilot and main experiment, no participants were excluded based on reaction times. Finally, the amounts of errors were simply counted.

3.4.3 Mouse trajectories

The x,y-coordinates data obtained from mouse tracking was also extracted, however, these data were first transformed and normalized. In order to facilitate this, the optimal path was calculated. This path was a vector based on the x,y-position of the mouse cursor when a trial was started, and the final position of the mouse cursor when the correct target was selected. The angle between this optimal path and a horizontal line was then calculated. Using this angle, all x,y-coordinates were then rotated counter clockwise, so that the actual mouse trajectory would run around a hypothetical horizontal axis. Next, using the transformed x,y-coordinates, the mouse trajectories were calculated. This was accomplished by subtracting the y-coordinate from the start position from each subsequent y position along the trajectory. Hypothetically, the trajectory of a perfect cursor movement would therefore be zero. The resulting value of the trajectory is therefore displayed as the total amount of pixels deviated from the optimal path. Additionally, because the total amount of pixels deviated became such a large number, the mean trajectory deviation per level was calculated, as well as its standard deviation.

Please note that the trajectory data is only available for the mouse trials in both the online pilot study and the main experiment. The touch screen, as stated earlier, does not require continuous contact between the finger and the screen, and the movement was therefore not recorded.

3.4.4 Subjective experiences

For the online pilot study, as the hyperlink to the experiment was published on either a forum, or a social networking site, there were quite a few participants who volunteered some subjective experiences. There were several comments on how entertaining the experiment was to play, ranging from 'fun to play' to 'very boring'. Additionally, there were several participants indicating they

had given up playing before the experiment was over; mostly this was because they did not find the experiment entertaining. Additionally, on the forums participants tended to report back their eventual score, and often claimed they had made very little errors. The latter indicates that the intended focus of the experiment, a speeded response over accuracy, was less well emphasized.

After the main experiment, participants offered less feedback than did the online participants. One thing that was mentioned by about half the participants was that they felt their arm was relatively fatigued after the touch screen part of the experiment. Furthermore, when the participant asked for the purpose of the experiment, most would indicate that they felt the touch screen was (much) faster to work with than was the mouse. This might be explained by the fact that the touch screen would sound a beep when touching the screen. Especially the interval between selection of the target, and pressing the Next-button in order to continue to the next trial felt much shorter than the same interval in the mouse condition. Whether or not this is indeed the case can unfortunately not be statistically proven, as these reaction times were not calculated in the experiment.

4 Results

4.1 Questionnaire

Exactly 50% of the participants in the online experiment used a desktop computer (n=43) and the other 50% used a laptop, furthermore, of the laptop users, 23 used a touch pad. The amount of hours spent behind the computer per day for the online participants is shown in Figure 4.1 and the age groups for the online participants, displayed in the bins used in the questionnaire, are shown in Figure 4.2.

The amount of hours spent behind the computer per day for the participants in the main experiment (n=12) is shown in Figure 4.3. The age of the participants was concentrated in the first age-bin, 19-25 years, with the exception of two who were between 26-32 years old.

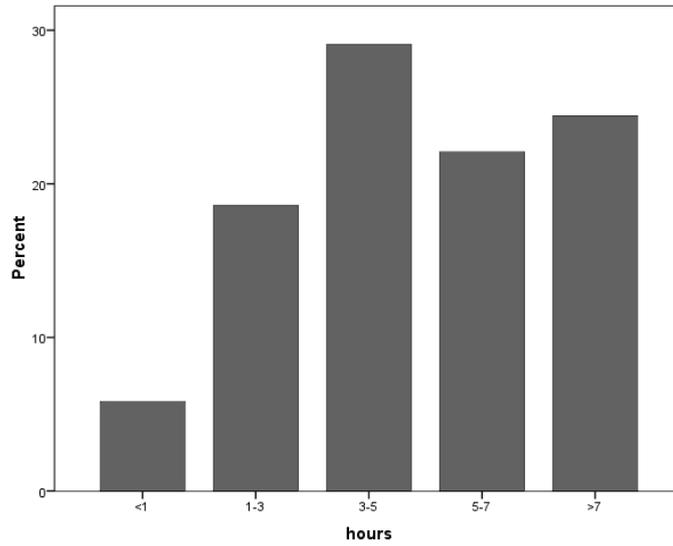


Figure 4.1. The hours spent behind the computer per day of the pilot study.

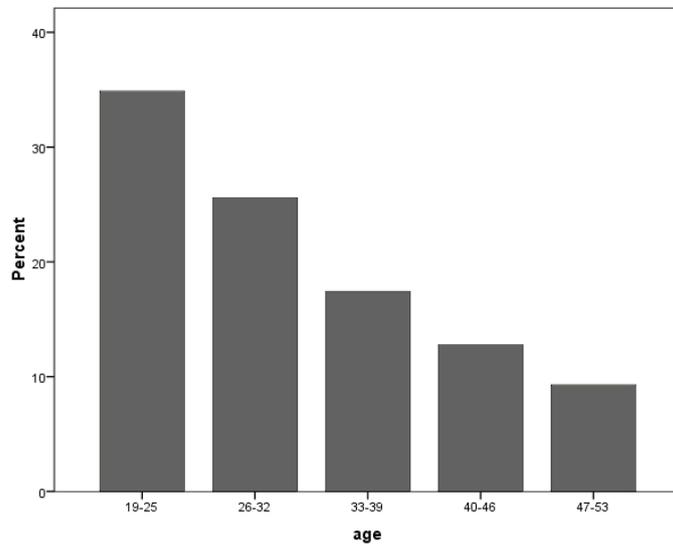


Figure 4.2. The age groups of the pilot study.

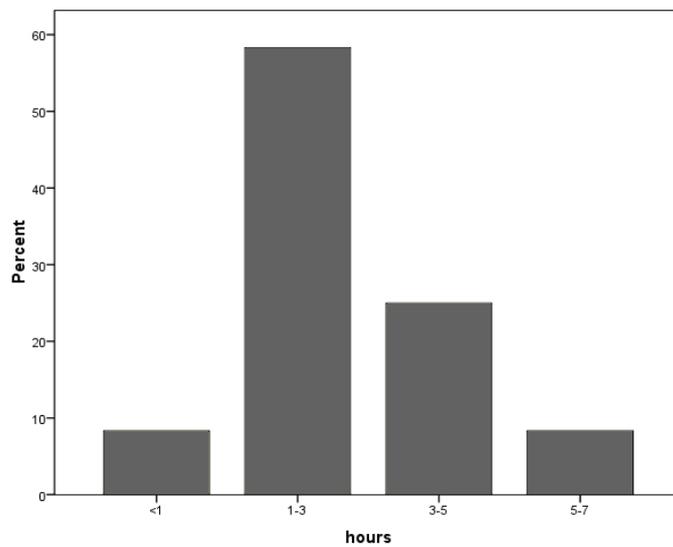


Figure 4.3. The hours spent behind the computer per day of the main experiment.

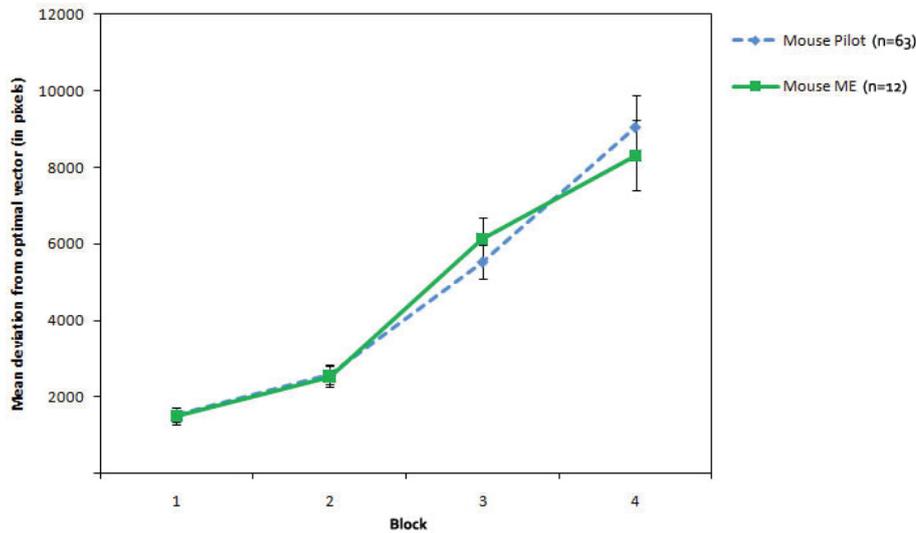


Figure 4.4. The maximum deviation from the optimal vector in pixels for the mouse condition, by experiment.

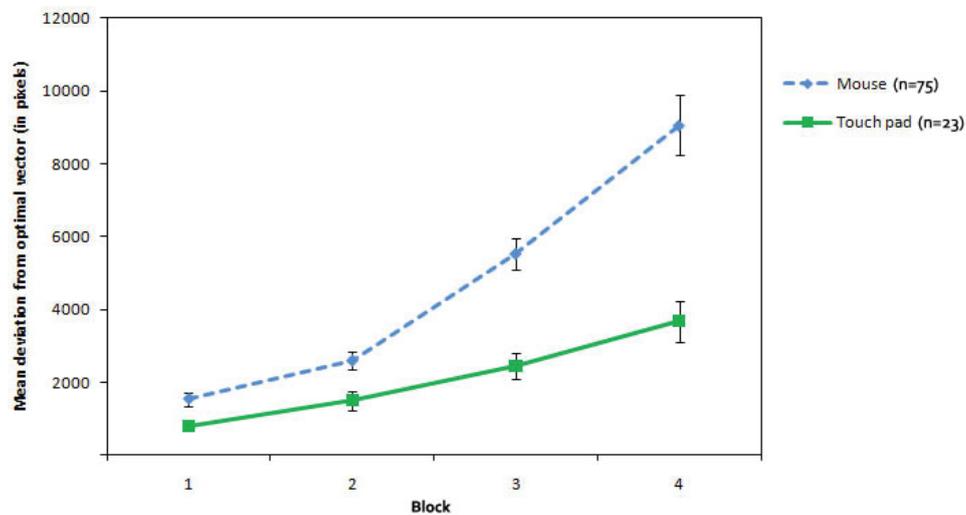


Figure 4.5. The maximum deviation from the optimal vector in pixels by input modality (mouse in both the online and main experiment vs. touch pad).

4.2 Mouse trajectories

Analysis of the mouse trajectories (MTs) obtained from the computer mouse and touch pad in the online experiment, as well as the computer mouse condition in the main experiment were analyzed based on the amount of pixels deviated from the optimal vector. Figure 4.4 shows the similarity in mean deviation from the optimal vector for the participants using the computer mouse in both the online experiment (Figure 4.4, Mouse Pilot) and the main experiment (Figure 4.4, Mouse ME). There was no significant difference between the observed deviations between the participants using a computer mouse in the online experiment and the main experiment. This is an indication that the participants' use of the computer mouse does not differ in terms of

deviations found in the mouse trajectories. In the analysis of the differences between the deviations from participants using either a computer mouse or a touch pad ($n=23$), the deviations from the computer mouse from both the online experiment ($n=63$) and the main experiment ($n=12$) are therefore analyzed together ($n = 75$).

An analysis of variance was conducted to compare the effect of input modality, the combined mouse data and the touch screen, on the mean deviation when difficulty increases. There was a significant effect of input modality ($F(3,144) = 35.44, p < 0.001$). A test of within-subjects contrasts show a J-shaped curve with a quadratic contrast ($F(1,47) = 19.67, p < 0.001$) for the combined mouse data, and it shows a linear contrast ($F(1,13) = 38.62, p < 0.001$) for the touch pad data (see Figure 4.5).

This suggests that when task difficulty increases, the amount the cursor deviates from the optimal vector increases, and that using a touch pad, the participants' mouse cursor travels in a more direct route from the 'Next'-button to the target than when the participant is using a computer mouse.

4.3 Reaction times

An analysis of variance was conducted to compare the effect of input modality, the combined mouse data and the touch screen, on the reaction times of correct trials when difficulty increases. There was a significant effect of task difficulty ($F(3,285) = 614.44, p < 0.001$). There is no significant main effect with of input modality (combined mouse data vs. touch pad) on reaction time. Looking at Figure 4.6 however, it seems like selection made using the touch pad are slower.

In order to analyze the effect of using a touch screen, a separate analysis of variance was conducted. The analysis of variance compared the effect of the touch screen on the reaction times of correct trials when difficulty increases. There was a significant effect of task difficulty ($F(3,33) = 150.85, p < 0.001$). A paired samples t-test was conducted to compare the reaction times on correct trials in the computer mouse and touch screen conditions in the main experiment. There was no significant result. However, although the results are not significantly different, there does

seem to be a trend indicating the touch screen is the fastest when selecting a target, and the touch screen is the slowest (see Figure 4.6).

4.4 Errors

An analysis of variance was conducted to compare the effect of input modality, the combined mouse data and the touch screen, on the amount of incorrect selections made (errors) when difficulty increases. There was a significant effect of task difficulty ($F(3,285) = 4.38, p < 0.005$). There is no significant main effect with of input modality (combined mouse data vs. touch pad) on the amount of errors made. Looking at Figure 4.7 however, it seems like the amount of errors made using the touch pad is lower. In order to analyze the effect of using a touch screen, a separate analysis of variance was conducted. The analysis of variance compared the effect of the touch screen on the reaction times of correct trials when difficulty increases. There was a significant effect of task difficulty ($F(3,33) = 3.13, p < 0.05$). A paired samples t-test was conducted to compare the of errors made in the computer mouse and touch screen conditions in the main experiment. There was no significant result. Looking at both Figure 4.6 and 4.7 there does seem to be a correlation between the speed of the input device and the amount of errors made.

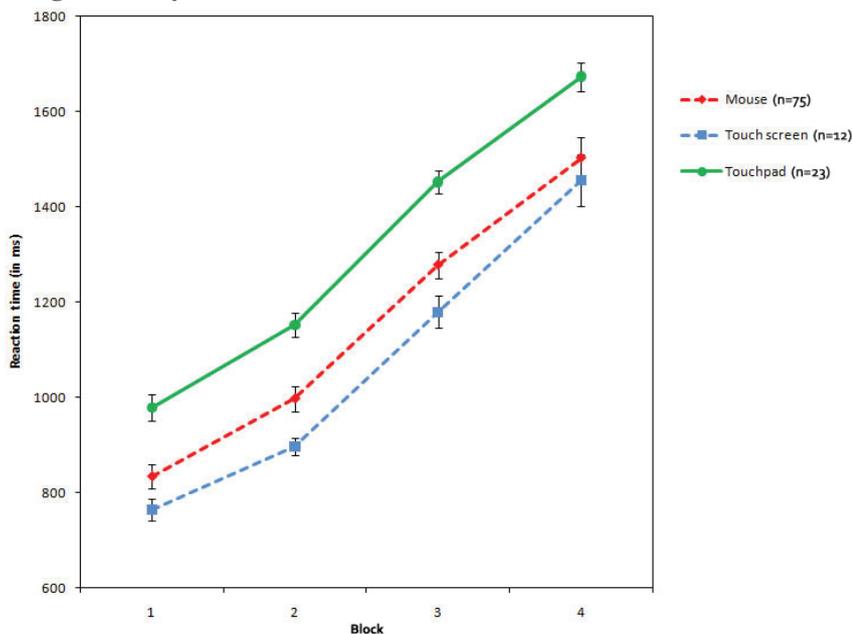


Figure 4.6 The reaction times on correct trials, by input device.

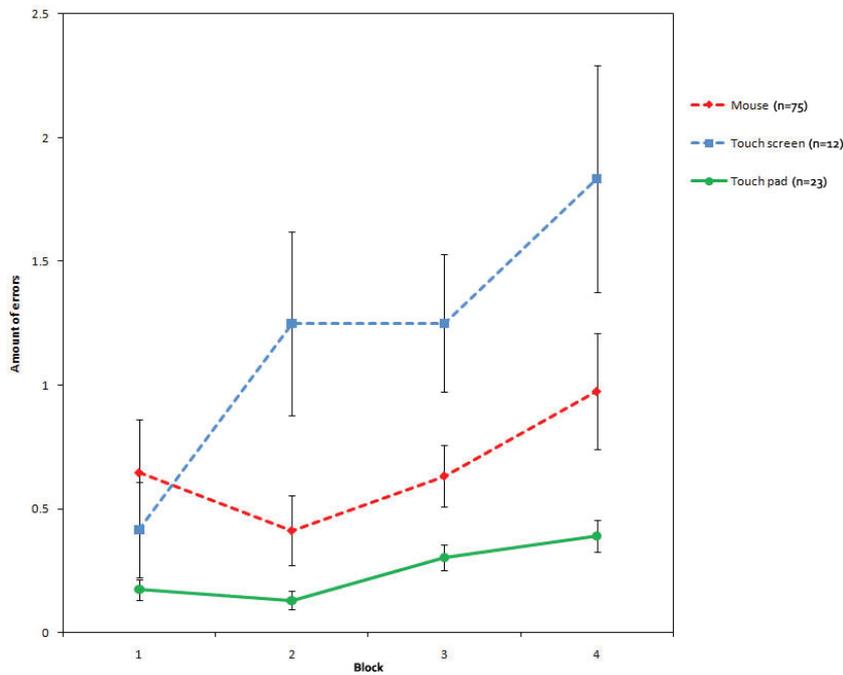


Figure 4.7. The amount of incorrect selections made (errors), by input device.

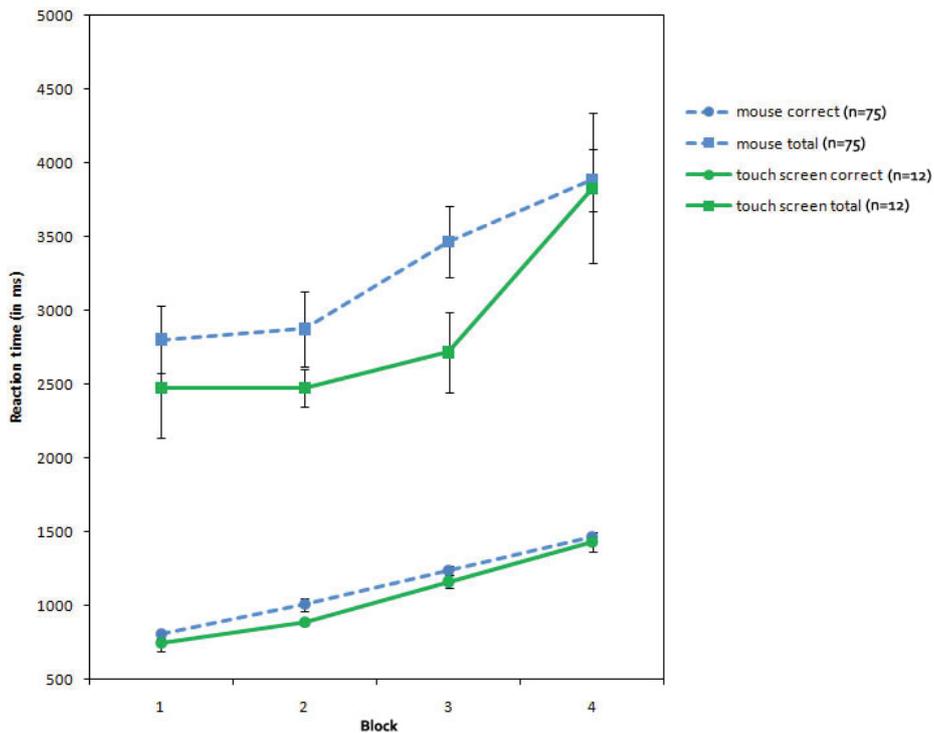


Figure 4.8. Differences between the mouse and touch screen conditions for both correct trial reaction times, and the total reaction time on incorrect trials.

4.5 Error recovery

Figure 4.8 shows the difference of the reaction times on the *correct* trials between the mouse and touch screen conditions, and the difference in the *total* reaction times (including the incorrect selection RT, undo RT and correction RT) between the mouse and touch screen conditions. A paired samples t-test was conducted to compare the total reaction times on incorrect trials in the computer mouse and touch screen conditions in the main

experiment. There was no significant difference.

However, when looking at the total reaction time on incorrect trials, it would seem that the touch screen has a large advantage over the mouse, in blocks one through three. There seems to be a larger than expected difference when looking at the total reaction times. In the fourth block of the touch screen condition, this difference disappears.

5 Discussion

This section discusses the results found in the experiments in contrast to the three hypotheses formulated, based on the literature described, which were:

- 1) The lack of a mouse cursor removes one processing step from the workflow and cause the user to work faster with a touch screen.
- 2) The use of a touch screen increases the amount of errors made because less visual processing is available to resolve response conflicts.
- 3) The touch screen allows for faster error recovery compared to the computer mouse.

5.1 Online experiments

One point of concern that must be addressed is that of the use of the internet as a platform for experimentation. There are several advantages to online experimentation, which include low cost, quick generation of large amounts of data, and no need to sit in on the experiment leaving the experimenter with more time to for example run an offline experiment. However, there are also a few disadvantages, which are described in detail by Skitka & Sargis (2006). Two of the disadvantages described are relevant for this thesis: 1) online participants may differ from 'offline' participants and 2) response rates are low, and therefore non-response error is high. These concerns are valid, however, they have also little influence concerning the online pilot study for several reasons. In case of the response rate, Skitka & Sargis (2006) are correct. The combined totals of registered users of the forums where the link to the experiment was hosted, at time of writing, is approximately 129.000. The online pilot study generated a total of approximately 100 *completed* participant files. This means that around 0.08% of the registered users completed the survey, which is a very small amount. However, many users register on a forum at some point and then never return, which makes the amount of *active* users a lot less than the number of registered ones. This is important to realize, as it both lessens the impact of the non-response on the one hand, but also eliminates a large group of possibly unmotivated participants. For example, when you recruit participants on forums, based on the forums topic, you expect the participants to belong to a specific group of people. To illustrate, if you wish to ascertain if professional versus amateur photographers both show the same change blindness effects, you might consider using a digital photography forum to recruit

your participants. However, many of the registered users may have been interested in digital photography at some point, but have never picked this up as a hobby. Therefore, the non-response of this particular group of people is actually preferred, rather than a disadvantage. In the case of the pilot study for this thesis however, motivation to participate was the largest concern, as the one of the reasons to choose for online experimentation was to generate data from a diverse group of participants.

That online participants may differ from 'offline' participants is for the purpose of the online experiment of little influence. When comparing the results of the mouse condition between the online pilot study and the main experiment, it is apparent that the mouse data is relatively similar. In the online pilot study no touch *screen* data could be collected, and in the main experiment no touch pad data was recorded. Additionally, none of the participants that were included in the analyses indicated he or she had any experience whatsoever with touch screen *monitors*. Because the groups were similar on the mouse condition, and almost all participants were or would have been novel to the experimental setup using a touch screen monitor, it is assumed that the results obtained from the main experiment can be used as a good indicator of the effects of touch screen *monitor* use in everyday computing for novel users. Even though the online participants were recruited from a heterogeneous population, the comparison of the computer mouse data showed that they do not differ in the basic control of the computer mouse in simple tasks.

One other minor concern put forth is that of technical constraints of the participants' hardware (Skitka & Sargis, 2006). Skitka & Sargis (2006) describe the problems of for example different browsers, internet connection speeds and resolutions as possible pitfalls in online experimentation. However, as described in the Experimental design section, the online experiment included code to avoid these pitfalls.

5.1.1 Unique participant identifiers

One particular concern that is not addressed by Skitka & Sargis (2006) is that of unique identifiers for participants. When conducting an experiment online, it is often difficult to identify which participants have already completed the experiment, and which ones have not. One way to implement a semi-failsafe identification method is through the logging of the participants' IP address. This method was used in the online pilot study in order to minimize overlap in

data. It is *semi-failsafe* for two reasons. First, there are two kinds of IP addresses: static, or dynamic. A static IP address remains the same every time a connection to the internet is made and a dynamic IP address changes whenever a new connection is made, or when the Internet Service Provider (ISP) changes it, usually on a 24-hour basis. This means, that some participants always have the same address, making it easy to see whether or not they participated earlier, however this also means that some participants may (unwittingly) try to participate once more using a different IP address. In the online pilot study, for the purpose of minimizing the mixing of participant data for first time players and recurring players, if the participants' IP address already existed, the questionnaire was skipped and the experiment was loaded immediately.

The second reason is based on the static IP addresses. Although these addresses remain the same, and are therefore useful in identify recurring participants, it is also possible that different participants use the same computer and are mistakenly identified as being one and the same person. Settings like this include for example families sharing the same computer, or multiple computers in a student flat sharing the same internet connection.

This can be solved by either implementing a signup method, where participants need to sign up for an account, uniquely separating them, or by for example sending e-mails containing a hyperlink to the experiment accompanied by a unique encrypted identifier which is then matched against a previously set up database to ensure the link is authentic. However, the former is likely to diminish the amount of participants as most will not eagerly go through a signup process to participate (voluntarily) in a strangers' experiment, whereas the latter can cost a fair amount of work for the experimenter.

5.2 Differences between input modalities

The first hypothesis put forth states that because of the lack of a mouse cursor one step is removed from the workflow and cause the user to work faster with a touch screen. The difference in reaction times on correct trials between the touch pad, computer mouse and touch screen conditions show a decrease in reaction times. The touch pad is the slowest, whereas the touch screen is fastest in selection times. Although participants often stated that the touch screen felt faster than the computer mouse, in literature it is often stated that this is difference is only marginally

significant (Forlines, Widgor, Shen, & Balakrishnan, 2007). Similar results were obtained in this study, and the touch screen seems to outperform the computer mouse in terms of reaction times on the correct trials.

The second hypothesis states that the use of a touch screen increases the amount of errors made because less visual processing is available to resolve response conflicts. When looking at the results of the error rates, this does indeed seem to be the case. The slower the input device, the lower the error rate. This conclusion is strengthened by the data obtained from the touch pad, which is slower than the computer mouse, and shows a lower error rate. Why this decrease in error rate coupled to an increase in reaction times occurs may be explained the theories discussed in the Theoretical framework section, on error monitoring and recovery (Rabbitt, 2002; Yeung, Botvinick, & Cohen, 2004). This theory states that a continuous flow of visual information is used to recover from an error, enabling participants to correct their errors in as little as 20-40ms (Rabbitt, 2002). However, this can also mean that whenever a target selection is fast, it is possible that not enough information is processed by the time the selection is made, which could be the reason behind the increase in error rate in the touch screen condition of the experiment.

Additional evidence for this process comes from the theory on eye- and cursor trajectories, which describes an increase of deviation based on too little visual information at the onset of movement. The amount of deviation can be exacerbated by the presence of distractors, and is assumed to be an indicator of response conflicts (Tipper, Howard, & Jackson, 1997; Van der Stigchel, Meeter, & Theeuwes, 2006). Since the deviations observed with the touch pad modality are smaller than those observed with the mouse, one would expect the amount of errors made to be lower with the touch pad, since it is assumed this indicates less response conflict. The results indicate that this may indeed be the case.

5.3 Error recovery

The third hypothesis put forth states, based on the first two hypotheses, that the touch screen allows for faster error recovery compared to the computer mouse. When an *incorrect* selection is made, there appears to be a marked difference in the total reaction time between the modalities. In the first 3 blocks, i.e. 2, 4 and 8 possible targets, the touch screen is faster when looking at *total* reaction times on incorrect trials (~500 ms.). This reaction time includes the incorrect selection time, the time it takes to press

the Undo-button, and the correction time. It would seem that, as hypothesized, the touch screen does introduce advantages over the computer mouse when correcting errors. Possibly because of the increased working speed, coupled to the concept of continuous visual processing (Rabbitt, 2002; Yeung, Botvinick, & Cohen, 2004), a difference becomes apparent. It must be noted that this increase in error recovery time does not compensate for the increase in making errors, because the total reaction time is still at least twice as high as the reaction time on a correct trial is. The cost of making an error is however somewhat lessened by this decrease.

Interestingly, the increased error recovery speed of the touch screen when compared to the computer mouse, disappears in the final block of the experiment. In the last block of the conditions of the experiment, the total amount of possible target locations is 12. A possible explanation for this may be that the amount of targets in the final levels interferes with the probe in visual short term memory (VSTM). That is, the probe has to be maintained in memory, in order for it to be matched against the different targets that exist. It could therefore be that the advantage of the touch screen, disappears because there is too much visual information to process, whereas when using the mouse, the slower speed is enough to not show this effect.

Another, simpler, possible explanation for the 12 item drop-off could be attributed to the participant's hand which could obscure the lower right quadrant of the screen. The targets and distractors in levels 1 through 3 were located primarily in the upper left quadrant. All participants in the main experiment were right handed.

5.4 Recommendations for touch capable devices

As stated in the introduction, touch screen technology is on the rise. There are more than a few different touch capable mobile phones or similar devices already, and these devices are very popular. Additionally, many more types of touch capable devices are currently being developed, or have recently been released to the market. However, as previous research indicates, and as is confirmed by the current study, these touch screen devices may be less useful than previously thought. The user is not much faster, and does in fact make more errors. The increase in errors could also be exacerbated by smaller target sizes, which, on mobile phones is more of a necessity than an aesthetic decision. A quick visual inspection of several touch

capable mobile phones (Apple iPhone 3GS, HTC G1 and Nokia XpressMusic 5800), seems to show two differences in user interface layout (amount of menu-items and the phones' back-buttons) which may underline the popularity of the devices. Based on the current study, one of the recommendations for touch screen application design, would be to limit the maximum amount of items displayed at any given time to no more than 12 (see Figure 5.1). However, it would seem that through the screen size limitations, the maximum amount of menu items is not much larger than this particular recommendation. For example, the amount of menu items displayed at maximum on the XpressMusic is 12, whereas on the G1, there are 16 menu items. The iPhone menu can hold up to 16 items as well, however the user may choose to display less.

Furthermore, although this is quite an obvious point: touch screen applications should have properly designed error recovery options. As there is an increase in error rate, the user should be aided as much as possible in recovering from an inevitable increase of errors. The XpressMusic for example has a button that reads 'close', which is used as a sort of 'back'-button. Although this label may be a bit misleading, the location of the button never changes, and what's more important, button itself is always visible when a user explores different menu options.

When using the G1 however, whenever an incorrect menu selection is made, the user can press either the 'home'-button to return to the phones' standard background. The user can also press the 'back'-button which has an equal function as the 'home'-button for first level menu items, and a proper back-function for second or higher level menu items. Whenever the user makes an incorrect selection from the menu, which requires one operation to display, for example opening the browser instead of opening the address-book, both the 'home'- and 'back'-button brings the user back to the background screen. The user then needs to open up the list with menu items again. This is an additional and unnecessary action, since the 'back' button could also have brought the user back to the menu itself, instead of the background. It must be noted, as these buttons are actual mechanical buttons, they are always located in the same place.

One additional observation from the main experiment must be mentioned with regards to touch screen monitors, which is the arm fatigue that was reported by at least half the participants in the main experiment. As stated earlier, the touch screen was already mounted on an inclined structure in order to minimize arm fatigue, but apparently it was still

less than optimal. This may cause problem when considering touch screen monitors in for example a normal office setting.

5.5 Future research

Based on the discussed literature and the current study, recommendations for future research can be made. First of all, it remains uncertain whether or not hand movements, in the case of touch screen usage follow the same general rules as do eye- and mouse cursor movements when it comes to response conflict. It was also shown in literature that hand movements indeed follow the same deviation pattern as eye or mouse cursor movements do (Farmer, Cargill, Hindy, Dale, & Spivey, 2007). However, as no data on the hand trajectories could be obtained in the experiment, this remains speculation. Therefore, repeating this experiment using a hand tracker for the touch screen condition may shed light on both the assumption that the touch screen introduces larger deviations. Furthermore, this could also shed light on whether or not the 12-item drop-off is based on cognitive limitations (possibly VSTM), or if it is a simple matter of the hand obscuring possible target locations. In the latter, one would expect to find a larger than normal increase in mean deviation of the trajectory, since the participant must move his or her hand out of the way to see the rest of the screen.

Additionally, the experimental setup of this thesis consisted of a matching task. When working with touch screen mobile phones, the user has to choose the proper item based on the probe's representation as it exists in memory. That is, the user may know what the icon for the internet browser looks like and must search for this icon based on the memory representation as opposed to an actual visual probe. This research could also be extended by using a more complicated graphical user interface (GUI), to more accurately resemble a real-world situation, or it may use an existing software package, for example the Windows 7 GUI. The latter example may be used to make recommendations for touch screen implementation for touch screen monitors.

On a more theoretical note, further research may focus on attempting to clarify why the touch screen is faster. To be more precise, is the touch screen faster because of a lack of the 'locate mouse cursor' step (discussed in the theoretical framework section) or is it faster based on a more primal sensory-motor coupling that allows for a swift selection. The latter is in essence a reasonable explanation, if you consider that it is much more natural to for example grasp a coffee-cup using your hand (touch screen analogy) or using a pair of oversized tweezers (computer mouse analogy).



Figure 5.1. Photographs of the mobile phones' menus mentioned in the discussion. From left to right: Iphone 3GS, Nokia XpressMusic 5800 and HTC G1.

6 Literature

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