Pressure as a Non-Dominant Hand Input Modality for Bimanual Interaction Techniques on Touchscreen Tablets

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Abstract

Touchscreen tablet devices present an interesting challenge to interaction designers: they are not quite handheld like their smartphone cousins, though their form factor affords usage away from the desktop and other surfaces, requires a user to support a larger weight and navigate more screen space. Thus, the repertoire of touch input techniques is often reduced to those performable with one hand. Previous studies have suggested there are bimanual interaction techniques that offer both manual and cognitive benefits over equivalent unimanual techniques and that pressure is useful as a primary input modality on mobile devices and as an augmentation to finger/stylus input on touchscreens. However, there has been no research on the use of pressure as a modality to expand the range of bimanual input techniques on tablet devices.

The first two experiments investigated bimanual scrolling on tablet devices, based on the premise that the control of scrolling speed and vertical scrolling direction could be thought of as separate tasks and that the current *status quo* of combining both into a single one-handed (unimanual) gesture on a touchscreen or on physical dial can be improved upon. Four bimanual scrolling techniques were compared to two *status quo* unimanual scrolling techniques in a controlled linear targeting task. The Dial and Slider bimanual technique was superior to the others in terms of Movement Time and the Dial and Pressure bimanual technique was superior in terms of Subjective Workload, suggesting that the bimanual scrolling techniques are better than the *status quo* unimanual techniques in terms of both performance and preference.

The same interaction techniques were then evaluated using a photo browsing task that was chosen to resemble the way people browse their music collections when they are unsure about what they are looking for. These studies demonstrated that pressure is a more effective auxiliary modality than a touch slider in the context of bimanual scrolling techniques. These studies also demonstrated that the bimanual techniques did not provide any concrete benefits over the Unimanual touch scrolling technique, which is the *status quo* scrolling technique on commercially available touchscreen tablets and smartphones, in the context of an image browsing task.

A novel investigation of pressure input was presented where it was characterised as a *transient* modality, one that has a natural inverse, bounce-back and a state that only persists during interaction. Two studies were carried out investigating the precision of applied pressure as part of a bimanual interaction, where the selection event is triggered by the dominant hand on the touchscreen (using existing touchscreen input gestures) with the goal of studying pressure as a functional primitive, without implying any particular application. Two aspects of pressure input were studied – pressure *Targeting* and *Maintaining* pressure over time. The results demonstrated that, using a combination of non-dominant hand pressure and

dominant-hand touchscreen taps, overall pressure targeting accuracy was high (93.07%). For more complicated dominant-hand input techniques (swipe, pinch and rotate gestures), pressure targeting accuracy was still high (86%). The results demonstrated that participants were able to achieve high levels of pressure accuracy (90.3%) using DH swipe gestures (the simplest gesture in the study) suggesting that the ability to perform a simultaneous combination of pressure and touchscreen gesture input depends on the complexity of the dominant hand action involved.

This thesis provides the first detailed study of the use of non-dominant hand pressure input to enable bimanual interaction techniques for tablet devices. It explores the use of pressure as a modality that can expand the range of available bimanual input techniques while the user is seated and comfortably holding the device and offers designers guidelines for including pressure as a non-dominant hand input modality for bimanual interaction techniques, in a way that supplements existing dominant-hand action.

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Last, but certainly not least, I would like to thank my family and friends for their unconditional love and support over the years. I have a special support net of parents, grandparents, aunts, uncles, siblings and friends without whom I'd be completely lost.

[1]Thanks also goes to Julie Williamson and Minko Daskalov for that particular contraption.

Education Use Consent

I hereby give my permission for this project to be shown to other University of Glasgow students and to be distributed in an electronic format. **Please note that you are under no obligation to sign this declaration, but doing so would help future students.**

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Declaration

Experiments 1 & 2 in Chapter 3 have been published in IFIP INTERACT 2013 [McLachlan and Brewster, 2013], co-authored with Stephen Brewster.

Experiment 5 in Chapter 5 has been published in CHI 2014 [McLachlan *et al.*, 2014], co-authored by Daniel Boland and Stephen Brewster.

Experiment 6 in Chapter 5 has been published in MobileHCI 2015 [McLachlan and Brewster, 2015], co-authored with Stephen Brewster.

The example system 'Finetuner', described in Chapter 5, has been published in MobileHCI 2015 [Boland *et al.*, 2015], co-authored with Daniel Boland and Roderick Murray-Smith. Daniel Boland and I jointly developed the concept for the FineTuner prototype.

This thesis only exploits those parts of these papers that are directly attributable to the author. All other referenced material has been given full acknowledgement in the text.

Chapter 1

Introduction

Touchscreen tablet devices (such as the Apple iPad, the Google Nexus 10 or the Microsoft Surface) present an interesting challenge to interaction designers: they are not quite handheld like their smartphone cousins, though their form factor affords usage away from the desktop and other surfaces. They can accept multitouch input and, by extension, bimanual input; however, users will often have to dedicate one hand to holding or supporting the device, constraining their ability to interact fully using two hands on the touchscreen. In general, the opportunities for bimanual input are constrained by the reach of the user's supporting hand. The challenge for designing bimanual interaction techniques for tablet devices is to enable coordinated two-handed input while the user is comfortably holding the device. This thesis explores the use of non-dominant hand isometric force (pressure) input to support interaction design in this context.

The ownership of tablet devices has been on the rise since 2012 [Ofcom, 2012] and almost doubled in 2014 [Ofcom, 2014]. Owners use their devices daily and despite the portability afforded by the form factor, use predominantly takes place in the home [Ofcom, 2012], often while sitting on the couch or bed [Müller *et al.*, 2012]. While this could also be said for smartphones and other small touch devices (such as mp3 players), a typical small form device can be held comfortably in the palm of the hand and can often be operated effectively using the thumb of the hand with which it is being held. This is not true for typical tablet devices. The form factor of these devices requires a user to support a larger weight and navigate more screen space. Thus, while the tasks being performed may be similar, the form factor of tablet devices requires either two hands, or a supporting surface, to interact.

When both hands are free (when the device is perched on a desk, worktop or even as the device rests on their lap) users can interact solely with their preferred hand or arbitrarily split a series of touch input gestures (single-touch and multitouch gestures, including simple taps) across two hands. In these cases it is possible to interact on the screen directly. However, when one hand is dedicated to holding or supporting the tablet, the degrees of freedom it has are reduced; now the supporting hand has a limited capacity for spatial movement and has to maintain a grip. Thus, the possibility of interacting with two hands on the screen is constrained and the repertoire of touch input techniques is reduced to those performable with one hand. Devices that support multitouch gestures can support simultaneous two-handed input, though to do so users must be able to touch the screen with both hands. From this, it is not clear how to design interaction techniques for tablet devices that take full advantage of the input channels available in the scenarios afforded by the form factor.

Previous studies suggest there are bimanual interaction techniques that offer both manual and cognitive benefits over equivalent unimanual techniques [Leganchuk *et al.*, 1998], though these studies have assumed static interactions in a desktop environment. This thesis will explore the use of non-dominant hand pressure input to enable bimanual interaction techniques for tablet devices that afford coordinated two-handed input while still allowing the user to comfortably hold the device.

1.1 Why Bimanual?

As human beings, we have natural bimanual motor skills that we have been using and perfecting our entire lives. This is not to say, however, that all two handed action is equivalent and certainly not all tasks are performed best using two hands. It is true that human beings can use both their hands simultaneously to perform tasks, though the addition of a second hand does not guarantee improved performance. It cannot be said, for instance, that writing with a pen in each hand improves the efficiency of writing; in fact, it is likely to make it more difficult. Human beings have evolved sophisticated bimanual motor skills that are strongest when each hand adopts an appropriate role [Leganchuk *et al.*, 1998].

A useful and well tested characterisation of such bimanual action is Guiard's *kinematic chain* (KC) model [Guiard, 1987]. Central to the KC Model is the cooperative and asymmetrical nature of bimanual action, meaning that when human beings perform tasks with both their hands they adopt different and complementary roles in order to do so. Guiard argues that the relationship between the dominant hand (DH) and non-dominant hand (NDH) is analogous to the relationship between a proximal and distal element in a kinematic chain, meaning that the two-hands function as serially assembled links, the implication of which being that the dominant hand will act in relation to the non-dominant hand.

Tablet interaction, as it currently exists, conforms to the KC Model insofar as the user's non-dominant hand sets the frame of reference for the action of their dominant hand by holding the device. Though, in much the same way as writing on a piece of paper - where the non-dominant hand holds the pages (sets the frame of reference) for the dominant hand to write on the page (the primary action of the task) - the non-dominant hand in tablet interactions primarily takes a supportive role. Designing tablet interactions that offer the user's non-dominant hand a more active role in the interaction has the potential to enable the user to use both hands to complete tasks in a richer and more effective way, or to enable effective input for richer and more complicated tasks.

There are potential manual and cognitive benefits to designing interaction techniques with an awareness of the KC model [Kin *et al.*, 2009, Leganchuk *et al.*, 1998] and there has also been early evidence suggesting that multitouch gestures that are based on human body movements that are not well documented or studied and can increase the risk of musculoskeletal disorders [Lozano *et al.*, 2011]. From this, the designers of tablet interactions could benefit from a better understanding of the ways in which human beings have evolved to use both their hands to interact with the world.

1.2 Why Pressure?

Isometric force, or pressure, input has been shown to be useful as a primary input modality on mobile devices [Brewster and Hughes, 2009, Wilson *et al.*, 2011, Wilson *et al.*, 2010, Heo and Lee, 2011] and as an augmentation to finger/stylus input on touchscreens [Ramos and Balakrishnan, 2005, Ramos *et al.*, 2004]. It has the property of adding another dimension that can be accessed continuously without large hand movements [Stewart *et al.*, 2010] and can be detected using simple Force Sensing Resistors (FSRs) that are flat and can be added to mobile devices without affecting the form factor. Since this research is interested in augmenting tablet devices with expressive input modalities that are accessible from the kinds of hold that such devices afford, it can be reasoned that pressure input would be advantageous for a number of reasons. Firstly, unlike accelerometers or gyroscopes for tilt control, pressure sensing does not require the manipulation of the angle of the device, which means the screen can be kept at an optimal viewing angle (or whatever angle the user desires). Secondly, pressure input can be distributed over a large area; entire touchscreens can be made pressure sensitive, as can the entire back or bezel of the device. This means that the same input modality can be accessed using either:

- One hand on the screen of the device;
- Two hands asymmetrically - where one hand controls pressure while holding the device and the other hand interacts with the touch screen;
- Two hands symmetrically - where both hands apply pressure input at the same time (which is the case with deformable devices, such as Gummi [Schwesig and Poupyrev, 2004]) or where both hands use pressure and touch at the same time.

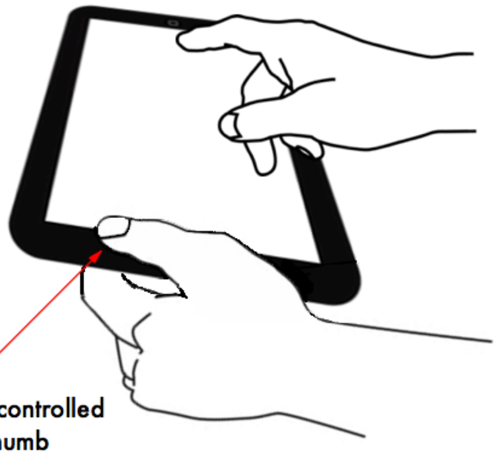


Figure 1.1: Pinch Grip. In all experiments decribed in this thesis, pressure is controlled using the thumb of the non-dominant hand with a "pinch-grip" on the bezel of the tablet device.

Thus, as a secondary input modality that could support multiple different holds and posture configurations, pressure input has some useful properties. However, these have not yet received much attention.

An alternative to a fully pressure sensitive device could be a fully touch sensitive device. With this, the user would be able to interact from any grip and in the various one and two-handed configurations outlined above, though such a device would introduce the requirement for the hands (or at least some of the fingers) to move about the x-y plane in order to interact. This may not be possible for the supporting hand as it needs to maintain a good grip to avoid dropping the device. Since the goal is to explore modalities that afford interaction while the device is being held, exploiting pressure input, which does not require changes in grip to interact but rather allows interaction while gripping, may be more suitable. In all experiments decribed in this thesis, pressure is controlled using the thumb of the non-dominant hand with a "pinch-grip" on the bezel of the tablet device (see Figure 1.1).

1.3 Tablet use in the home: setting the context

Scrolling intensive tasks, such as social networking, looking up information, listening to music, watching TV/movies and browsing online stores are recurrent on tablet devices in the home [Müller *et al.*, 2012]. Furthermore, it is not uncommon for large online collections, such as personal and streaming based media collections like Netflix or Spotify, or online

Figure 1.2: Bang & Olufsen BeoSound 5. The side-mounted dial is used to scroll the on-screen content.

stores like Amazon, to contain hundreds of thousands, if not millions, of items. While the need for browsing through large collections can be mitigated providing good recommendations or by improving search there is always a need to have an efficient and appealing way to access 'your stuff' in its entirety: Cunningham *et al.* [Cunningham *et al.*, 2004] note that, in relation to browsing personal music collections, users perform what may essentially be an undirected linear search until something strikes them as what they want to hear at that moment, suggesting that browsing through entire collections is a valuable task to support serendipitous discoveries when no particular target is in mind.

However, scrolling using conventional techniques can quickly become cumbersome. On tablet devices, unimanual scrolling involves repetitive flick and or drag gestures on the touch-screen or by performing similar rotational movements (flicking and dragging) on a physical dial (such as on the Bang & Olufsen BeoSound 5 (see Figure 1.2 [1])). While this technique is straightforward to learn, it only offers very coarse control over scrolling speed and scrolling long lists can be time consuming. There are several alternative strategies users can adopt to find items in long lists such as searching or filtering the list using text input, or by jumping directly to a letter in an alphabetically ordered list (such as on Apple iOS devices), or by employing a separate fast scrolling slider (as on Google Android devices), though these techniques often require the user to know what s/he is looking for in advance, which is not always the case.

[1] The physical dial on the Bang & Olufsen BeoSound 5 is used to scroll through a music library displayed as a circular list on the screen. This kind of scrolling behaviour is also exhibited on scroll-wheels on mice and keyboards.

1.4 Research Questions

This thesis will answer four research questions. The first two are specifically related to whether using pressure as part of a bimanual input technique can improve scrolling performance on tablets. The second two research questions aim to study pressure as a functional primitive, without implying any particular application. In doing so, use of pressure as an auxiliary input modality (one that supplements, rather than replaces touch interaction) can be investigated by evaluating its impact on existing DH input techniques and *vice versa*.

RQ 1: Can bimanual input techniques improve scrolling performance on tablet devices?

RQ 2: Can novel input modalities (such as pressure) improve performance for bimanual tablet based scrolling interactions?

RQ 3: How accurate are people at performing a bimanual combination of NDH pressure and DH touch input on tablet devices?

RQ 4: How accurately can people maintain NDH pressure while performing DH touch input on tablet devices?

1.5 Thesis Statement

Tablet users will often have to dedicate one hand to holding or supporting the device, constraining their ability to interact fully using two hands on the touchscreen. This thesis asserts that non-dominant hand pressure can be used to effectively expand the range of available bimanual input techniques for touchscreen tablets. The results show that users can effectively control non-dominant hand pressure input and simultaneously interact using their dominant-hand, while still holding the device.

1.6 Thesis Structure

Chapter 2, *Literature Review*, reviews the literature on both bimanual HCI, considering the attempts to exploit the natural bimanual motor skills of human beings in the design of computer interfaces and the importance of considering the role each hand plays in relation to the other in order to do so; and on the use of pressure as an input modality in HCI, the precision of applied pressure using various pressure sensitive input devices, the unique properties that pressure input has and the way in which these properties could be useful to design.

Chapter 3, *Bimanual Scrolling*, presents the results of two studies investigating performance of bimanual an unimanual scrolling techniques on a touchscreen tablet device using a linear targeting task. The purpose was to establish whether splitting the control of scrolling speed and scrolling direction across two hands resulted in improved performance when compared to *status quo* unimanual scrolling techniques. This chapter contributes to RQ1 and RQ2.

Chapter 4, *Browsing Media Collections*, evaluates the same scrolling techniques from Chapter though in a more realistic media browsing task. The purpose of this chapter was to establish whether the bimanual scrolling techniques provided any benefit over *status quo* unimanual scrolling when evaluated using a more realistic task. This chapter also contributes to RQ1 and RQ2.

Chapter 5. *Transient Pressure*, builds on the arguments about the properties of pressure input discussed in the literature review and presents a novel model of pressure input where it is characterised as a *transient modality*, one that has a natural inverse, bounce-back and a state that only persists during interaction. This chapter also presents the results of two studies investigating the precision of applied pressure as part of a bimanual interaction, where the selection event is triggered by the dominant hand on the touchscreen (using existing touchscreen input gestures) with the goal of studying pressure as a functional primitive, without implying any particular application. This chapter answers RQ3 and RQ4.

Chapter 6, Discussion and Conclusions, reviews and summarises the research in this thesis. Limitations of the research are discussed and possibilities for future research are proposed.

Chapter 2

Literature Review

2.1 Bimanual Human Computer Interaction

Generally, the design of bimanual interaction techniques in HCI has involved identifying cases where there are a number of serial unimanual actions in performing a task, decomposing those tasks then in some way distributing their execution across two hands. In doing so, gains in performance can be explained either by the fact that the two tasks can now be performed in parallel or by the fact that each hand is now in a 'home' position, which decreases the time taken to switch between the two tasks.

Early work on bimanual HCI assumed that users would be sat at a desktop, interacting through various peripheral devices placed on the desk. Leganchuk, Zhai and Buxton [Leganchuk *et al.*, 1998] give an overview and valuable insight into much of this early work. In surveying the literature on bimanual HCI, they observe that there are contrasting views on whether bimanual interaction techniques actually provide any benefit. The contrasting experimental results are exemplified in studies by Buxton and Myres [Buxton and Myers, 1986] and a study by Dillon *et al.* [Dillon *et al.*, 1990]. Buxton and Myres performed two experiments that evaluated the benefits of bimanual input for compound tasks: one investigating a positioning-scaling task and another a navigation-selection task. The interaction techniques were designed in such a way that both hands were providing continuous input. The positioning-scaling task was designed such that the non-dominant hand (NDH) scaled an object while the dominant-hand (DH) manipulated the object's position. The results suggested that the majority of participants performed some of the tasks in parallel, without prompting and that the level of parallelism correlated to performance improvement. Buxton and Myres concluded that because participants demonstrated the ability to perform both tasks in parallel, almost immediately and without prompting, no significant additional cognitive load was imposed by the use of bimanual input. For the navigation-selection task, the NDH controlled scrolling (while navigating through a document) while the DH selected pieces of text. Despite the fact that the same levels of parallelism were not observed, the bimanual technique was still significantly faster than the traditional one-handed technique. The authors attribute this performance gain to the fact that each hand stayed in the 'home position' for its own particular task, meaning that no switching was required between scrolling and selecting, which enabled participants to carry out the task more quickly. From these studies two distinct benefits of bimanual input can be observed: parallelism with low-cognitive load and reduced switching times between sub-tasks.

In contrast to the results of Buxton and Myers were those of Dillon *et al.* [Dillon *et al.*, 1990]. Dillon *et al.* conducted an experiment that examined performance in a compound line drawing task. Participants were required to select an item from a menu and then draw a line elsewhere on the screen. One technique was a standard GUI unimanual method where one cursor would be switching between menu selection and drawing. There were also two variations of a 'two-cursor' method that employed the use of both hands, one controlling a cursor over a menu for selection and the other for drawing (menu size was varied for the two conditions). In this experiment, a small but insignificant advantage of two-handed input was found over unimanual input.

From these results, Leganchuk, Zhai and Buxton [Leganchuk *et al.*, 1998] state, "we must conclude that the benefits of two-handed input are task and design dependent. Clearly, a deeper level of understanding of human bimanual function is needed for the successful design of two-handed computer input."

By analysing the interaction techniques from the early experiments with respect to Guiard's Kinematic Chain (KC) model [Guiard, 1987], they observed that the bimanual techniques from the Buxton and Myres study conformed to the model and showed advantage over unimanual equivalents, while those from Dillion *et al.* did not conform to the model and showed little or no advantage over equivalent unimanual techniques. From this, they concluded that two hands are not always better than one, and that when designing bimanual interaction techniques, it is important to do so using the KC model.

Guiard's Kinematic Chain Model [Guiard, 1987] (discussed in detail below) is a useful and well tested characterisation of bimanual action. The model is based on an analogy to a series of abstract motors. When two or more motors are assembled in series, they form a kinematic chain, the most common example of which is an arm. Each link in the chain has a proximal element (e.g. the elbow) and a distal element (e.g. the wrist). Due to the fact that the two are physically attached, the distal element must configure its movement relative to the output of the proximal element. In this case, the wrist must move relative to the position of the elbow. Central to the KC Model is the cooperative and asymmetrical nature of bimanual action, meaning that when human beings perform tasks with both their hands they adopt different and complementary roles in order to do so.

Guiard argues that vast majority of real life human manual acts belong to the bimanual asymmetric class and that asymmetry in action is the rule and symmetry the exception. Meaning that not only are there a set of tasks, such as opening a bottle or slicing food, that are obviously bimanual and asymmetric, but that even supposed unimanual tasks, such as throwing a dart or brushing your teeth, are essentially bimanual actions (where the non dominant hand plays a supportive, postural role). Tasks where both hands perform essentially the same role either in phase (such as rope skipping or lifting) or out of phase (such as typing or rope climbing) are the exception to the rule.

The bimanual interaction techniques used in Dillion *et al.* were variations of a 'two-cursor' method, where each cursor carried out an independent, not cooperative, role (one to select from the menu using the NDH and one to draw a line using the DH) which resulted in both hands having symmetry in input – the opposite of what Guiard's model suggests. Whereas the interaction techniques from Buxton and Myres used different input modalities for each hand, which afforded asymmetric interaction. In the navigation selection task, participants scrolled the document with their NDH using a touch sensitive strip while the DH selected the required text with a mouse and in the positioning and scaling task, the DH positioned the object using a mouse while the NDH scaled the object using a 1-D physical slider bar. In both cases the NDH was performing a task with an input modality that was coarser than that of the DH.

Leganchuk, Zhai and Buxton [Leganchuk *et al.*, 1998] also present results of a study in which users were asked to carry out an object selection task (to draw a bounding box around different shapes) using both bimanual and unimanual techniques. In the study there was one unimanual and two bimanual techniques. The unimanual technique was based on traditional WIMP GUI method and involved participants first selecting the desired tool from the toolbar using the cursor and then dragging on the surface, over the object, to create the bounding box. Upon release, the standard handles from most drawing applications appeared at the four corners of the bounding box, which allowed participants to make any necessary adjustments. The first bimanual technique involved the participants stretching the bounding box with two hands. The tool is selected from the menu in the same way as the unimanual technique, only once the tool is selected two cursors appear at opposite corners of the bounding box. The participant could then control each of the cursors with each of their hands allowing them to both scale and position the bounding box simultaneously. The second bimanual technique was based on the Toolglass technique introduced by Bier *et al.* [Bier *et al.*, 1993]. Using this technique, the participant scales and positions the bounding box with two hands in the same way as the first bimanual technique, except, until the tool is selected the NDH controls the position of the (in this case semi-transparent) toolbar. This means that, before the tool is selected, the participant can control the positions of the toolbar using his or her NDH and select the appropriate tool using their DH. Once the tool has been selected, the toolbar disappears and the NDH takes control of one corner of the bounding box and the participant can begin scaling and positioning it. Since the toolbar, when available, is always under control of the NDH, it can easily be repositioned to reduce the amount of distance the DH has to travel to make the selection, which offers a clear Fitts' Law advantage. The Toolglass technique was previously evaluated in a study conducted by Kabbash *et al.* [Kabbash and Buxton, 1994]. Their experiment compared four different interaction techniques for the task of drawing coloured line segments between dots. This task required a menu selection of the correct colour and then a drag to create the line from one dot to the next. They found the Toolglass technique, which conformed to the KC model, to be superior over all the other techniques as it required fewer motor operations and the tools and drawing area were always in the same visual space, thus eliminating the possibility of divided attention. The experimenters noted that users were using their NDH hand the most when using the Toolglass technique. Yet, as the results suggest, this did not hinder performance.

The results from Leganchuk, Zhai and Buxton's study [Leganchuk *et al.*, 1998] showed both bimanual techniques outperform the unimanual technique. The data also suggested that as the task becomes more cognitively demanding the difference in the performance between the one and two handed techniques will become more pronounced. They conclude that to give the users the ability to use both hands and manipulate the tasks at a natural level is a "logical and inevitable trend of a broad range of HCI applications".

2.1.1 Models of Bimanual Action

Guiard's Kinematic Chain Model is a useful and well tested characterisation of bimanual action [Guiard, 1987]. The cooperative and asymmetrical nature of the KC model describes that when human beings perform tasks with both of their hands they adopt different and complementary roles in order to do so. Guiard argues that vast majority of real life human manual acts belong to the bimanual asymmetric class and that asymmetry in action is the rule and symmetry the exception. Meaning that not only are there a set of tasks, such as opening a bottle or slicing food, that are obviously bimanual and asymmetric, but that even supposed unimanual tasks, such as throwing a dart or brushing your teeth, are essentially bimanual actions. It is impossible to demonstrate that the NDH has no role in these tasks, in which it is likely that the NDH plays a supportive, postural role.

Guiard argues that the relationship between the dominant and non-dominant hand is analogous to the relationship between a proximal and distal element in a kinematic chain. The implication being that the DH will act in relation to the action of the NDH. The model can be summarised in the following principles (for a person who is right-hand dominant):

- *Right-to-Left Spatial Reference*: The left hand sets the frame of reference in which the right hand acts.

- *Left-Right Scale Differentiation*: The granularity of action of the left hand is much coarser than the right hand (i.e. the movement of the left is macrometic while the movement of the right is micrometric)
- *Left-Hand Precedence in Action*: the sequence of motion is left hand followed by right-hand
- *Right-Hand Dominance*: People will show a subjective preference for the right-hand over the left hand in action.

A common example that is used to support the Kinematic Chain Model is that of handwriting. When a person writes on a piece of paper, their NDH plays an important supportive role by holding or moving it into place for the DH as it writes. The pattern can also be observed in the way that people chop vegetables, or put toothpaste on their toothbrush. As a model, it describes well a number of common, everyday tasks.

While Guiard's KC model [Guiard, 1987] is a useful and well tested characterisation of human bimanual action, it only models a particular class of bimanual action: asymmetric bimanual action. However, Latulipe and others [Balakrishnan and Hinckley, 2000], [Latulipe, 2006], [Latulipe *et al.*, 2006] have demonstrated that there is a class of common HCI tasks that can be modelled as symmetric bimanual actions. An interaction is symmetric "whenever the two hands work together, in the same frame of reference, at similar levels of spatial and temporal resolution" [Latulipe *et al.*, 2006]. Latulipe *et al.* evaluated symmetric shape-manipulation techniques involving simultaneous rotation and translation for object placement, image alignment [Latulipe, 2006] and for spline manipulation [Latulipe *et al.*, 2006]. In all three studies, two mice were used to provide two symmetric input channels (one for each hand) and in each they found that the symmetric techniques significantly outperformed the asymmetric and single mouse techniques.

Latulipe [Latulipe, 2006] describes a model of symmetric bimanual interaction in which tasks can be thought of and broken down into symmetric components and distributed over two hands. The model consists of a set of heuristics, designed to facilitate decision making regarding whether an interaction could benefit from being implemented with symmetric bimanual input. The model is summarised in four points: "

- Symmetric interaction is a superset that includes asymmetric interaction. An interface that affords symmetric interaction can be used asymmetrically, but the reverse is not usually true.
- Symmetric interaction requires symmetric devices, or a specialized single device that allows both hands to interact together;

- Symmetric interaction requires bilateral function symmetry. Pressing a button with a given finger on one hand should activate the same functionality if the same finger on the other hand presses a button;
- Symmetric interaction should involve a unified task, where the two hands work together to manipulate a single object. This means the two hands should work in the same frame of reference."

One of the caveats of the model is that in order to perform symmetric interaction effectively, a user requires device symmetry. Therefore, when using both hands on the touchscreen, symmetric bimanual input is possible and effective as is demonstrated when 'pinch-to-zoom' and 'rotate' touch gestures are performed with two hands on touchscreen devices. However, the scenarios that are being studied in this thesis have an inbuilt asymmetry to them: when one of the user's hands is dedicated to holding or supporting the device, several of the symmetric criteria outlined above are not possible. "Device symmetry" is broken because one hand has to maintain a grip. This also makes "bilateral function symmetry" difficult as well since both hands do not have the same capacity for spatial movement.

It is interesting to note that the interaction techniques evaluated in Leganchuk, Zhai and Buxton [Leganchuk *et al.*, 1998] combined the best of both asymmetric and symmetric bimanual input. When selecting the tool, the interaction techniques afford asymmetric interaction, e.g. when the NDH positions the Toolglass under the DH cursor. However, when scaling the bounding box, the interaction becomes symmetric: a cursor for each hand is placed at opposite corners of the box, enabling participants to position and scale the bounding box using two hands in a symmetric manner. Although they do not recognise this in the paper, it suggests that symmetric and asymmetric bimanual action exist in harmony, not conflict, with one another and that the design of successful bimanual interaction techniques will take into account the properties of both the input modalities and the task in order to establish whether symmetric or asymmetric input should be used.

2.1.2 Bimanual Interaction on Touch Screen Devices

Multitouch devices are, by definition, capable of accepting bimanual input. By sensing multiple points of contact on the screen, touchscreens allow the user to distribute input across fingers, on one or more hands. Small handheld touchscreen devices are designed primarily for one-handed interaction [Pascoe *et al.*, 2000] and larger tablet devices tend to use similar interaction metaphors. This succeeds in providing consistency across devices, though does not take advantage of the additional interaction space present on larger tablets. Bimanual techniques are required that have been designed specially with portable touchscreen devices in mind.

Kin et al. [Kin *et al.*, 2011] demonstrated that bimanual marking menus improve selection performance over one handed marking menus on small handheld touchscreen devices (in this case an iPod Touch). Participants made selections on the marking menus using both of their thumbs while the device was held in both hands in landscape mode, affording symmetric bimanual input – since both hands contributed equally to the interaction. There is no evidence to suggest that they would be beneficial in contexts where one hand is constrained by holding the device, while another acts as the primary input.

Brandl *et al.* [Brandl *et al.*, 2008] tested different combinations of bimanual pen and touch input, designed using Guiard's KC model, on a touchscreen table. They found the combination of *pen and touch* to be superior in terms of in terms of speed, accuracy, and user preference compared to *pen and pen* or *touch and touch*, echoing the results from Leganchuk, Zhai and Buxton [Leganchuk *et al.*, 1998] that KC informed bimanual interaction techniques work best when each hand operates in a different modality. However, this study did not provide a baseline comparison to demonstrate that the bimanual techniques provided any benefit over a unimanual equivalent. Benko *et al.* [Benko *et al.*, 2006] demonstrated the use of dual finger bimanual selections to increase pointing precision on touchscreen tables. They compared their techniques against a simple pointer offset and found that the bimanual techniques, which enabled users to slow the speed of the cursor in various ways with the NDH while controlling the position with their DH, improved performance. Both of these studies assume that both hands are free to interact, providing little understanding of what might be enable bimanual input while the device is being held.

Despite the fact that one hand is often required to hold the device, it can do so in a variety of ways. As the hand may be in contact with the bezel and back of the device, these areas could be augmented with additional hardware to enable interaction. For example, RearType [Scott *et al.*, 2010] includes a physical keyboard on the back of a tablet PC. Users hold it with both hands while entering text, thus avoiding an on-screen keyboard and graphical occlusion by the fingers. LucidTouch [Wigdor *et al.*, 2007] is a proof-of-concept see-through tablet that supports simultaneous touch input on the front and on the back of the device. Users hold the device with both hands, with thumbs on the front and remaining fingers on the back. The device is small enough that users can reach the entire back allowing multitouch interaction with both hands while fully supporting the device. However, the arm-mounted camera currently makes this approach impractical. Gummi [Schwesig and Poupyrev, 2004] is a prototype bendable tablet that allows bimanual interaction by deforming the device by gripping its edges. Kildal and Wilson [Kildal and Wilson, 2012] investigated the effect of material properties for bendable interactions on mobile devices and found that while stiffness did not significantly affect performance, users had a strong preference towards sofer materials. These examples provide useful information when considering symmetric interactions, though do not address scenarios where the hands take asymmetric roles.

Wagner *et al.* [Wagner *et al.*, 2012] designed BiPad, a user interface toolkit to introduce asymmetric bimanual interaction on tablets. It is designed to work on existing touchscreen tablets, without any additional hardware. The users' non-dominant hand (NDH) can execute commands on special regions of the screen that are accessible while they are holding the tablet. For example, users can activate contextual menus to control the zooming and rotation of maps by tapping, gesturing or making chords with their NDH, while their dominant-hand (DH) selects items from the menus, or controls the position of the zooming and rotation, simultaneously. They found that the bimanual techniques did improve performance over unimanual techniques. Their aim was to provide a general way to provide bimanual interaction on tablet devices and actual behaviour of the NDH would vary from application to application. The paper presents two studies and a prototype bimanual tablet interaction toolkit: BiTouch and BiPad. In a preliminary study the authors investigated the different holds that people use when interacting with a tablet device while standing and identified 5 that could be used for simultaneous support and interaction and noted that users frequently adjust their grip of the device to avoid fatigue. They outline BiTouch - a design space to describe the ways in which users hold tablet devices and which suggests directions for designing new bimanual interaction techniques. The BiPad interaction techniques use the BiTouch design spaces to introduce new bimanual affordances for touchscreen tablet devices in the form of chords, taps and gestures performed by the thumb and fingers of the supporting hand on the screen. A controlled experiment was carried out to evaluate these techniques, the results of which suggested that taps outperformed the one handed control on both landscape and portrait; chords and gestures in portrait only; and thumbs outperformed fingers but were more tiring and less stable.

It is clear that one of the main advantages of the BiPad interaction techniques – the fact that they are able to be performed on a current generation tablet device without any hardware modifications - is also a significant drawback. Enabling NDH interaction on the touchscreen means the user has to reach over the bezel of the device, an issue that the authors do not discuss. Since the time of publication, new commercial devices have been made available on the market that have smaller bezel areas (such as the iPad Air 2) that would make it easier to reach the screen. The approach taken in this thesis is to augment the existing bezel area of the tablet devices with pressure sensors.

2.1.3 Summary

The goal of the work described in this thesis is to explore ways to enable simultaneous two-handed input while the user is comfortably holding the device and to demonstrate the properties of pressure input that make it suitable as an auxiliary input modality for this task. Scenarios in which one hand holds/supports the device while the other operates the touchscreen – where the input capabilities of each hand are be asymmetric – will be considered. Therefore, techniques where two hands apply pressure in a symmetric fashion (such as in [Kildal and Wilson, 2012], [Schwesig and Poupyrev, 2004]) are out of the scope of this investigation.

2.2 Pressure in HCI

This literature review will show that by using pressure as part of a bimanual interaction, we have the opportunity to split the control of pressure movement and interface selection across two hands and thus remove the complications that arise when the selection mechanism and pressure input are controlled through the same input channel [Ramos *et al.*, 2004, Wilson *et al.*, 2011, Wilson *et al.*, 2010].

Studies of pressure input in HCI have largely focused on how many distinct levels of pressure a user can accurately apply within a given pressure range. This range, known as the 'pressure space', gives an indication of the bandwidth of a pressure based interaction [Wilson *et al.*, 2010]. User performance in this type of 1-dimensional pressure based linear targeting (PBLT) task has been shown to be highly accurate for up to 8-10 pressure levels, while stationary with visual feedback [Ramos *et al.*, 2004, Cechanowicz *et al.*, 2007, Mizobuchi *et al.*, 2005, Shi *et al.*, 2008, Wilson *et al.*, 2010] and while mobile with both visual and non-visual feedback [Wilson *et al.*, 2011].

PBLT is a useful task for the evaluation of pressure based interaction techniques as it allows researchers to compare human ability to control pressure at different levels, under varying conditions and with different modes of feedback. These studies have not only been used to measure control of pressure-based input in an abstract sense, but also to evaluate performance in terms of targeting-based interactions: where a user controls a cursor by applying pressure, as a primary input modality, with the goal of selecting targets or menu items. Subsequently, the results reported by studies of this type are often coloured by factors that arise solely from the specific assumptions made about the mapping of pressure to function.

For instance, in addition to *how* pressure input in controlled (through a stylus [Ramos *et al.*, 2004], by squeezing force-sensitive areas on devices such as mice [Cechanowicz *et al.*, 2007] or the bezel of mobile devices [Wilson *et al.*, 2010, Wilson *et al.*, 2011]), and the particular configuration of the pressure space (such as the total size of the space in Newtons and the way in which it is split into targets); the particular control mapping (or force-to-motion mapping) and selection mechanism (way in which a selection is made) are key factors that influence the metrics of success.

The design recommendations for pressure-sensitive interfaces are based on the assumptions of menu traversal and target selection and the metrics used to determine success often pivot on the successful performance of a selection gesture, or how to move a cursor through the menu space, rather than human ability to control continous pressure input. While this is important to the design of pressure-based interfaces when considered as a *single primary input modality* (the only modality through which a user provides input to the system), it is less useful in the context of pressure as an auxiliary or supportive input modality where selections could be completed through another input channel, or where menu selection is not the ultimate goal (for instance, with continous scrolling or zooming).

2.2.1 Control Mappings

The two most common force-to-motion mappings are Positional control and Rate-based control. With Positional control, how hard a user presses dictates the position of the cursor within the interaction space. In a 1-dimensional menu, this means that as the user applies more pressure, the cursor will move further forward through the menu (and *vice versa*). In Rate-based control, how hard the user presses dictates the speed at which the cursor moves through the menu: as the user presses harder, the cursor will move though the menu faster (and *vice versa*). With a single pressure sensor, Positional control can support bidirectional movement (pressure can be applied and released to move forwards and backwards, respectively). Rate-based control requires the cursor to loop from the end of the menu back to start, or the addition of a second pressure sensor, to support bidirectional movement.

Rate-based control generally outperforms Positional control in controlled PBLT tasks. For instance, Wilson *et al.* [Wilson *et al.*, 2011] compared Rate-based to Positional control, in both static and mobile conditions, with both visual and audio-only feedback for up to 10 levels in a 3.5N pressure space. Both Positional and Rate-based control had similar levels of accuracy across conditions, though Rate-based control was significantly faster and had significantly lower subjective workload. In addition, feedback did not affect accuracy using Rate-based control when mobile: error rates were similar with visual feedback (ER=3.2%) to those with audio-only feedback (ER=3.0%). Shi *et al.* [Shi *et al.*, 2009] found rate-based control to be superior to positional control for object rotation. In an integrated 2D movement and translation task, with a pressure augmented mouse (where pressure controlled rotation and mouse movement controlled translation) they found that participants performed better with a higher degree of simultaneous action using Rate-based control.

However, as Wilson [Wilson, 2013] notes "[Rate-based control] is not as suitable for measuring the precision of applied pressure, as it is an artificial mapping, but it is useful for understanding how the usability of a pressure-based interaction, like targeting or menus, can be improved". Since one of the goals of this is to investigate *how accurately* people can control pressure while holding a tablet device – as opposed to how accurately they can select from a menu, which would be a completely valid, though totally different, research question – Rate-based control will not be used and instead this thesis will focus on Positional control.

2.2.2 The Selection Problem

Studies that employ a PBLT task to evaluate the use of pressure as a primary input modality under various conditions (static or mobile, finger or stylus, etc) inevitably have to consider the way in which those menu items are selected. In a wider context, performing an explicit selection on an interface widget is still central to the way in which we design user interfaces: we do have a user interface that operates without a discrete 'select' mechanism. However, pressure, as an input modality, suffers from a shortcoming concerning selection: it does not provide a convenient opportunity for a selection event that also takes advantage of the fact that it is a continuous input modality. Selections can be made by crossing a pressure threshold (such as applying more pressure to select a capital letter on a keyboard [Brewster and Hughes, 2009]), where it is reduced to a binary modality; or selections can be detected by imposing some conditions on user behaviour, such as with Dwell and Quick Release [Ramos *et al.*, 2004, Wilson *et al.*, 2011, Wilson *et al.*, 2010].

With Dwell, users apply pressure to navigate to a target and linger on that target for a particular length of time (usually 1 second), which the system registers as a selection. With Quick Release, users release their grip quickly when on a target, which the system registers as a selection. Generally, the Dwell technique results in fewer selection errors than Quick Release [Ramos *et al.*, 2004, Wilson *et al.*, 2010], though at the expense of speed (as the dwell time impacts the overall selection time). However, errors for the Dwell technique can occur when participants accidentally linger for too long on the wrong target [Wilson *et al.*, 2010].

For instance, Ramos *et al.* [Ramos *et al.*, 2004] used a PBLT task to assess stylus based pressure input. They included four different selection techniques - Dwell, Quick Release, Click (clicking a button on the barrel of the stylus) and Stroke (making a spatial movement to the right). They found that users could accurately select targets in a pressure space with up to 6 levels and that the Quick Release technique was most effective. Both the Click and Stroke techniques were problematic in their study as they interfered with the pressure input, causing errors to be made as selections were performed. They suggest that, since movement and selection take place on the same input channel (as opposed to a mouse, in which movement and selections take place on orthogonal input channels), designers should minimise the interference between movement and selection phases, and suggest Dwell or Quick Release as suitable techniques for doing so.

Wilson *et al.* [Wilson *et al.*, 2010] investigated the use of pressure to perform menu selections on mobile devices using a PBLT task. Comparing both visual and audio only feedback, using both Quick Release and Dwell for up to 10 levels in a 3.5N pressure space and found that while Quick Release (with a good detection algorithm) was fastest, Dwell was more accurate. They also stress the importance of a well calibrated, linearised pressure sensor for accurate performance.

The Dwell technique is problematic as it is slows the interaction: typical dwell times last a second [Ramos *et al.*, 2004, Wilson *et al.*, 2011, Wilson *et al.*, 2010] . However, considering the accuracy benefits of Dwell that have been reported [Ramos *et al.*, 2004, Wilson *et al.*, 2011, Wilson *et al.*, 2010], the dwell-time may be an appropriate trade-off. Yet, this overlooks a second problem with Dwell: in real world systems a user must be in constant motion to avoid unintended selections. Since the selection mechanism is based on dwelling on a target, the interface does not afford the kind of interaction where a user may linger over targets while in the process of finding what s/he is looking for. Lingering is a selection in a dwell based pressure interface and has been shown to cause selection errors [Wilson *et al.*, 2010]. Increasing dwell times (to 2 seconds, for instance) may mitigate the problem, though this slows the interaction further while only increasing the potential lingering time by a second.

The Quick Release technique is problematic as it is difficult to detect effectively: it is often difficult to tell what menu item the user initiated the Quick Release selection on when as samples can be erroneously taken from the sensor as the user is performing a selection [Wilson *et al.*, 2010]. There is also evidence that Quick Release is subjectively preferred over Dwell despite the loss of accuracy [Ramos *et al.*, 2004]. It is possible that by creating models of the user that the quick release technique could be improved; by learning how the user behaves when s/he wants to make a selection, the system will better be able to discriminate between movement gestures and selection gestures.

Cechanowicz *et al.* [Cechanowicz *et al.*, 2007] compared Dwell, Quick Release and Click selection techniques in a PBLT taks using pressure augmented mouse and found that users were faster with a higher level of control and gave higher subjective rankings with the Click technique. The Click functionality was provided through the left-mouse button and their augmented mouse allowed users to operate the pressure sensor and provide selections using different fingers. Their click technique was further decoupled from that of Ramos [Ramos *et al.*, 2004]. However, there were still higher levels errors for Click, suggesting that further decoupling of pressure input from selection could be required in order to improve performance.

2.2.3 Applications of Pressure in HCI

A number of studies have used pressure to create novel interaction techniques with particular hardware setups, for specific applications domains. For instance, Holman *et al.* [Holman *et al.*, 2013] developed a prototype mobile device exploring the use of auxiliary pressure input using squeeze gestures along the side of the device for one-handed mobile interaction, which they called Unifone. Three squeeze positions were explored – Top, Middle and Bottom – to support coarse auxiliary input for four common mobile interaction techniques: scrolling, map navigation, text formatting and application switching. Their results suggest that pressure input is most effective when complementing the action of the primary thumb input, as opposed to replacing it altogether. They also suggest that "the fingers are extremely poor at providing fine grained input", however without sufficient detail about the pressure mapping and pressure space used, it is difficult to put this observation into a wider context.

Spelmezan *et al.* [Spelmezan *et al.*, 2013] attached pressure sensors to the side of an iPod touch in a similar configuration to Holman *et al.*, although they name their system SidePress. Their prototype supports bi-directional navigation capabilities and mode switching via a light-press, heavy-press and continous rate-based input across two sensors (one at the top and one at the bottom on the side of the device). Details about the magnitude of the pressure space are hinted at in a figure caption – approximately 1N for a light-press and 5N for a hard-press. Their event vocabulary was evaluated and results suggest that participants can control the SidePress events with a high level of accuracy (90%) and that, when compared to normal flick-style touch gestures, their input vocabulary is more efficient for scrolling long distances (though, normal touch was better for scrolling shorter distances). In the scrolling task, the light-press and hard-press events enabled users to jump in the document in the document (12.5% jump for the light-press while the hard-press navigated to the top or bottom of the document, depending on direction). It is not clear from their results whether performance gains using side press were due to use of these shortcuts (which are essentially two-state buttons), or whether participants used the rate-based continous pressure input, and whether that enabled them to navigate the document more efficiently.

Hoggan *et al.* [Hoggan *et al.*, 2012] investigated the use of pressure to provide synchronous haptic communication during phone calls, which they call "Pressages". Users could squeeze on the side of a mobile phone, and the amount of pressure applied would be mapped to vibrations on the recipient's device. A pressure space of approximately 6 Newtons was divided into 4 levels and selections were made using the Quick Release technique, with both visual and non-visual (vibrotactile) feedback. The effect of the different feedback modalities were evaluated on pressure input performance using a controlled targeting study. The results suggested that the combination of visual and vibrotactile produced the fastest task completion times, though the vibrotactile only condition produced higher levels of accuracy. The authors speculate that the vibrotactile provides complete eyes free feedback and that the coupling of pressure and vibrotactile may be more "direct and simple for users because they are both forms of the same modality". Pressages were evaluated in a longitudinal study, where couples were each given a prototype device that enabled them to transmit pressages during phone calls with one another. Users expressed greetings, presence and emotions through Pressages, and all of the participants chose to include pressages in every conversation with their partner.

While these studies provide useful data on the use of pressure for particular application domains, using particular pressure space configurations in comparison to equivalent *status quo* techniques, they rarely provide justification for that configuration or experimentally vary the parameters in a way that gives insight into how they affect performance. For instance, Spelmenzan *et al.* [Spelmezan *et al.*, 2013] show that SidePress can outperform flick-based touch in longer scrolling, though since only one input vocabulary was tested, it is difficult to know what elements were helpful for performance; or whether having more pressure levels in the Pressages [Hoggan *et al.*, 2012] pressure space would have made them more (or less) expressive. The next section will outline the properties of pressure input that are being masked by the current experimental paradigms which may be useful to design and which this thesis aims to investigate in a controlled manner.

2.2.4 Properties of Pressure Input

Pressure is an input modality with no obvious or inherent selection mechanism. When using a stylus, coupling the movement and selection phases in a PBLT task improves performance [Ramos *et al.*, 2004], however decoupling the movement and selection phases with a mouse has also been shown to improve performance [Cechanowicz *et al.*, 2007]. While the performance benefits of coupling movement and selection may be device dependent, doing so confounds our understanding of how well people can control pressure input independently of a menu selection task, limiting the design space for which the results can be of use. As discussed above, a major component of the results concerning pressure based input in HCI are concerned with the particular selection mechanism and force-to-motion mapping used - both of which are relevant to pressure based menu selections and not the control of pressure more generally. Considering the control of pressure independently of menu selection issues would provide results that could be used by designers and practitioners to design novel pressure based interaction techniques that go beyond traditional menu selections and take advantage of some of the unique properties that pressure input has.

Pressure has a unique combination of properties that distinguish it from the current repertoire of input modalities, though have not been explicitly studied or discussed in the literature. For instance, pressure has a natural inverse. Whenever pressure is applied, a release of pressure follows. Pressure input has a natural ebb and flow that may be useful in design, which is masked when selection events are imposed. When a user performs a dwell gesture, s/he hovers on a target, it is selected and the interface updates. When this happens the menu may disappear, the screen may update or in some cases the entire suite of widgets may change (another facet of interface design that is understudied with Dwell and Quick Release techniques). However, after the selection has been made, s/he is still applying the same amount of pressure as before, despite it having no effect on the interaction. The use of pressure thus becomes inconsistent. Before the selection, applying and removing force on the interface affected the state of the widget in equal and opposite ways; however, after the selection, the pressure applied to the interface does nothing. The selection will occur, the interface will update and the amount of pressure that the user is applying has to be ignored.

The natural inverse that pressure has is worth considering as it embodies one of the fundamental principles of user interface design: Permit easy reversal of actions. This has long been acknowledged as a fundamental principle of user interface design [Shneiderman and Plaisant, 2005]. In doing so, it relieves anxiety, since the user knows that errors can be undone, and encourages exploration of unfamiliar options. Like dials or knobs, there is an obvious and natural way to reverse an action. When one turns a dial, it is obvious that the turning it the opposite way is a possibility, that is an intrinsic property of the modality. Pressure has a similar inverse. It is obvious and natural that when one applies force to an object, the force can be released.

Pressure input also has a second property: ‘Bounce-Back’ [Ghazali and Dix, 2005]. Bounce back is a property that makes a device or modality return to its original state or position soon after the user has relinquished control. In the case of a joystick, a user can move the joystick freely about 2 dimensions though when they release the stick, it always returns to the centre. Pressure input has a similar property - when a user stops applying force to a pressure sensor it returns to its original state of having zero force applied to it.

Pressure falls within the class of modalities within the intersection of natural inverse and bounce back. When a modality with natural inverse also has the property of bounce back, it creates the property of a modality that forces the inverse to occur whenever control is released. Any spring-loaded device with natural inverse also exhibit this property. A spring-loaded dial or knob would behave in the same way - when the user stops interacting with the device, it will return to its original position via each state that exists in between. The dial will rotate back to its original position. This is the same for a spring-loaded slider bar. When you combine natural inverse with bounce back there is no way to reach the original state without moving back through all of the states in-between. This is in contrast to a joystick. A joystick will return to the centre position when you let go. However, it will not pass through any other states on the way. The action that previously occurred is not reversed (you do not retrace the joystick’s path back to the centre), it is just neutralised. It is true that the exact path taken by a pressure sensor is not completely revisited either (the sensor will not visited higher pressure states again before returning to a no pressure state), but it will pass through all the states between the current position and zero as the pressure is released.

In [Ramos *et al.*, 2004], the one technique that decoupled the movement and selection phases - the 'Click' technique, using which selections were made my clicking a button the barrel of a stylus - performed poorly. However, this was because both the movement and selection events were controlled from a single input device in such a way that resulted in instability in pressure input when the 'Click' was performed. When controlling a cursor using a mouse or a trackpad, both movement and selections are necessary and they are also decoupled. A mouse or trackpad that used Dwell or Quick Release to perform selections would be absurd. With these input devices, we have designed in an explicit and discrete selection mechanism to complement the movement controls. Furthermore, results obtained using selection techniques such as Dwell or Quick Release and a Rate based force-to-motion provide useful data about how pressure can be used to select items from a menu, but provide litte data about different ways in which pressure could be used to affect the interface. For instance, since the Dwell selection technique involves detection 'dwell times' for selections, it explicitly rules out interaction techniques that involve maintaining pressure over a longer period of time (say 10-30 seconds). By tightly coupling selection techniques and the control of pressure, so we gain little knowledge about different ways that pressure could be used beyond traditional menu selections. In addition, PBLT targeting studies often require trials to be started when no pressure is applied, we gain little knowledge about how well users can move up and down the pressure space by both applying and releasing pressure.

2.2.5 Configurations of the Pressure Space

Stewart *et al.* [Stewart *et al.*, 2010] demonstrated the importance of considering the characteristics of the particular pressure sensing hardware before making assumptions about optimal configurations for the pressure space. Previous work [Ramos *et al.*, 2004] suggested that with a linear pressure mapping, participants demonstrated less control at low levels in the pressure space and many alternative mappings have been suggested in order to correct for this. For instance, Cechanowicz *et al.* [Cechanowicz *et al.*, 2007] suggest using a quadratic mapping centred at the lower range; Ramos and Balakrishnan [Ramos and Balakrishnan, 2005] use a parabolic-sigmoid transfer function; McCallum *et al.* use a logarithmic discretisation function to map key pressure to character; Shi *et al.* found a fish-eye discretisation function to be superior. This is in contrast to Srinivasan and Chen [Srinivasan and Chen, 1993], who found that error in controlling normal forces of contact with rigid objects with visual feedback remains approximately constant for all measured target forces.

Stewart *at al.* [Stewart *et al.*, 2010] show that the hardware configurations used in previous work were likely to have not given true linearity. They demonstrated that with a properly calibrated sensor – an operational amplifier as specified in the datasheet for an Interlink Electronics Force Sensing Resistor (FSR) – a linear mapping worked best. They also compared several different pressure input poses for handheld mobile devices (in this case, an iPhone Sandwich [Essl *et al.*, 2009]). Four poses were tested: Front-on-table, where pressure is applied via the index finger on the front of the device as it rests on the table; Grip, where pressure is applied to the device via a pinch-grip between the thumb and index finger; Front, where pressure is applied using only the thumb on the front (while the left hand holds the device); Back, where pressure is applied using only the index finger on the back of the device. They conclude that the Grip input pose is optimal in terms of performance and user preference as well as showing that input performance is possible with a much larger 12N pressure space than has been considered in previous work.

In this work, we use investigate the control of pressure using bimanual strategy, completely decoupling the the movement and selection events by splitting them across two hands on a tablet device. By allowing the non-dominant hand to control pressure input using a pinch-grip on the bezel of the device and the dominant hand to perform primary input, not only do we get a clearer understanding of how well users can control pressure input, we do so in the context of existing tablet based interactions - allowing us to augment, rather than replace, existing interaction techniques.

2.2.6 Summary

The majority of studies on pressure input in HCI have focused on how many distinct levels of pressure a user can accurately apply, as a primary input modality using his or her DH and has been shown to be highly accurate for up to 8-10 targets while stationary with visual feedback [Wilson *et al.*, 2010, Wilson *et al.*, 2011, Cechanowicz *et al.*, 2007, Ramos *et al.*, 2004, Mizobuchi *et al.*, 2005, Shi *et al.*, 2008] and while mobile with both visual and non-visual feedback [Wilson *et al.*, 2011]. These studies have revealed several factors that are thought to be central to the effective use of pressure, particularly on mobile devices. These are: the number of digits used, the levels of pressure required and the feedback provided [Wilson, 2013]. However, since pressure is often considered as a primary input modality, a significant factor in a number of these studies is the particular selection mechanism (Dwell or Quick Release) and the force-to-motion mapping (Positional or Rate based) used, which is often influential in the effectiveness of a pressure-based interaction. Performance using these techniques in the studies described was still high and neither are untenable for effective one-handed pressure input. However, they do not provide guidance on other aspects of pressure control that may be useful in interaction design, such as how accurately people can maintain pressure over time and how well they can both apply and release pressure within the pressure space.

2.3 Conclusions

The ownership of tablet devices has been on the rise [Ofcom, 2012] and despite the portability afforded by the form factor, use predominantly takes place in the home [Ofcom, 2012], often while sitting on the couch or bed [Müller *et al.*, 2012]. Scrolling intensive tasks, such as social networking, looking up information, listening to music, watching TV/movies and browsing online stores are recurrent on tablet devices in the home [Müller *et al.*, 2012]. Furthermore, it is not uncommon for large online collections, such as personal and streaming based media collections like Netflix or Spotify, or online stores like Amazon, to contain hundreds of thousands, if not millions, of items. Though, services like this often only provide access to the collections via search, eliminating the opportunity for browsing - a key method for serendipitous discovery [Cunningham *et al.*, 2004].

The form factor of tablet devices requires a user to support a larger weight and navigate more screen space and when one hand is dedicated to holding or supporting the tablet, the degrees of freedom it has are reduced; now the supporting hand has a limited capacity for spatial movement and has to maintain a grip. Thus, the repertoire of touch input techniques is reduced to those performable with one hand. From this, it is not clear how to design interaction techniques for tablet devices that take full advantage of the input channels available in the scenarios afforded by the form factor.

The research reviewed in Section 2.1 shows that there are bimanual interaction techniques that offer both manual and cognitive benefits over equivalent unimanual techniques and the research reviewed in Section 2.2 shows that pressure is useful as a primary input modality on mobile devices and as an augmentation to finger/stylus input on touchscreens. However, there has been no research on the use of pressure as a modality to enable bimanual interaction techniques on tablet devices. The Research Questions that this thesis will address focus on using bimanual interaction techniques, with pressure as a NDH input modality, in order to address two separate, but related, aspects of tablet use in the home. Firstly, to address whether bimanual interaction techniques can make the task of browsing large media collections more efficient. Therefore, Research Questions 1 & 2 ask:

> *RQ1: Can bimanual input techniques improve scrolling performance on tablet devices?*

> *RQ2: Can novel input modalities (such as pressure) improve performance for bimanual tablet based scrolling interactions?*

Secondly, to study the use of pressure more abstractly, as a functional primitive to expand the range of bimanual input techniques on tablet devices. Therefore, Research Questions 3 & 4 ask:

> *RQ3: How accurate are people at performing a bimanual combination of NDH pressure and DH touch input on tablet devices?*

> *RQ4: How accurately can people maintain NDH pressure while performing DH touch input on tablet devices?*

Chapter 3

Bimanual Scrolling

On tablet devices, scrolling speed and direction are controlled by performing flick and drag gestures using a single finger on the touchscreen, or by performing similar rotational movements (flicking and dragging) on a physical dial (such as on the Bang & Olufsen BeoSound 5 (see Figure 1.2) [1]). While this technique is straightforward to learn, it only offers very coarse control over scrolling speed and scrolling long lists can be cumbersome. There are several alternative strategies that users can adopt to find items in long lists, such as searching or filtering the list using text input, jumping directly to a letter in an alphabetically ordered list (such as on Apple iOS devices), or by employing a separate fast scrolling slider (as on Google Android devices). However, these techniques often require users to know what they are looking for in advance, which is not always the case. While the need for scrolling through large collections can be mitigated by finding better ways to provide good recommendations or by improving search, there is always a need to have an efficient and appealing way to access 'your stuff' in its entirety. Therefore, Research Questions 1 asks:

> *Can bimanual input techniques improve scrolling performance on tablet devices?*

Scrolling is composed of two variables: the scrolling speed and the scrolling direction. The purpose of this chapter is to establish whether there is a benefit in splitting the control of scrolling speed and scrolling direction over the two hands. By allowing a user's NDH to set the scrolling speed while their DH controls scrolling direction, it may be possible to give them more control over the interaction. We split control of speed and direction across the two hands in this order because, in terms of the KC Model [Guiard, 1987], we can say that the NDH is setting the frame of reference (the speed) for the action of the DH (the

[1] The physical dial on the Bang & Olufsen BeoSound 5 is used to scroll through a music library displayed as a circular list on the screen. This kind of scrolling behaviour is also exhibited on scroll-wheels on mice and keyboards.

movement and selection). A number of scrolling techniques are described whereby existing scrolling methods (drag and flick gestures on a touchscreen or on a dial) are augmented with a speed control mechanism. Control of the scrolling speed is given to the NDH using either a pressure sensor or a touchscreen slider, and the control of direction is given to the DH using touchscreen drag gestures or a rear mounted physical dial. Therefore, Research Question 2 asks:

> *Can novel input modalities (such as pressure) improve performance on bimanual tablet based scrolling interactions?*

This chapter describes two experiments investigating bimanual scrolling on tablet devices. Experiment 1 compares bimanual scrolling techniques to *status quo* unimanual scrolling techniques in a controlled linear targeting task, as well as investigating the role of different DH and NDH modalities. Experiment 2 exclusively investigates scrolling techniques that involve pressure input. Specifically, it compares different pressure spaces and pressure mappings.

3.1 Experiment 1: Modalities for Bimanual and Unimanual Scrolling

This study was based on the premise that the control of scrolling speed and vertical scrolling direction can be thought of as separate tasks and that the current *status quo* of combining both into a single one-handed (unimanual) gesture on a touchscreen or on physical dial can be improved upon. The experiment sought to determine whether splitting the control of scrolling speed and scrolling direction over two hands, in accordance with the KC Model [Guiard, 1987], could improve user performance in a one-dimensional scrolling task on a touchscreen tablet device.

3.1.1 Input Methods

For direction control, two existing scrolling methods were chosen: drag gestures on a touchscreen and a free rotating physical dial. Therefore, the direction control modalities were Touch and Dial.

A pressure sensor was chosen as one of the speed control modalities, since pressure has been demonstrated to be a useful modality for the control of speed (for rate based cursor control) [Wilson *et al.*, 2011]. A pressure sensor can be mapped well to the control of speed using an accelerator metaphor, where increasing the force will increase the speed and *vice versa*.

Furthermore, isometric force input is useful as an input modality on mobile devices [Wilson *et al.*, 2010, Wilson *et al.*, 2011, Brewster and Hughes, 2009] and as an augmentation of finger/stylus input on touchscreens [Ramos *et al.*, 2004] (although not tested in the NDH). It can be detected using FSRs that are flat and can be added to different locations on a device without changing its form factor.

Since there is a combination of physical and touchscreen input for direction control, a touchscreen slider was included for speed control. It did not require the NDH to perform a precise task (just one dimensional movement) and it could be mapped well to speed control: up to increase the speed, down to decrease.

3.1.2 Interaction Techniques

There were six interaction techniques evaluated in the study: two unimanual and four bimanual.

Unimanual Techniques

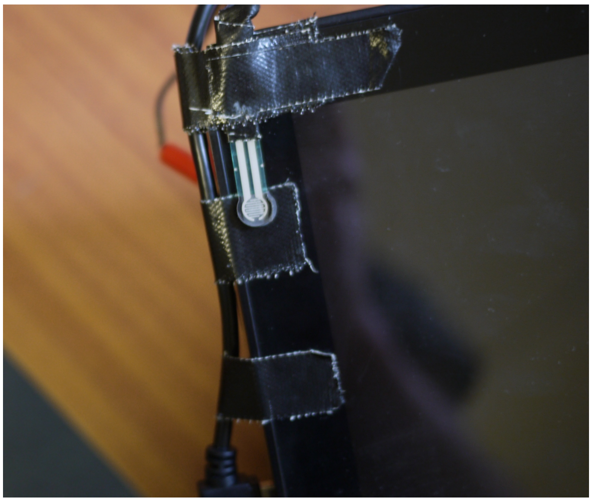
There were two unimanual techniques: Unimanual Touch and Unimanual Dial, in which scrolling direction and scrolling speed were controlled with one hand. The Unimanual Touch technique was the same as that found on current touchscreen tablets and phones and was used as a control condition for the experiment. To scroll, participants could either drag or perform a flick gesture with their finger on the touchscreen, which would cause the viewport to scroll. Flicking faster increased the scrolling velocity. The Unimanual Dial technique was similar insofar as participants could rotate the dial to scroll through the list, or ‘flick’ the dial to scroll more quickly. The unimanual techniques are summarised below:

Touch This interaction technique requires one hand only. It operates like other touchscreen scrolling mechanisms: using flick and drag gestures on the screen. Dragging a finger on the screen will scroll in the direction that the finger is dragged, flicking on the screen will cause the content to scroll faster.

Dial This interaction technique requires one hand only and uses the dial mounted on the rear of the device (see Figures 3.1a and 3.1b). It operates in the same way as the side mounted dial on the Bang & Olufsen BeoSound 5 (see Figure 1.2). Rotating the dial caused the interface to scroll, clockwise down, anti clockwise up. By performing flicks using the dial, the interface will scroll faster, much in the same way as it does for normal touchscreen scrolling.

(a) Dial Mounted on the Rear of the Tablet

(b) Griffen Power Mate Dial with Plastic Extension



(c) Force-Sensing Resistor Mounted on Bezel of Tablet

Figure 3.1: Experimental Apparatus.

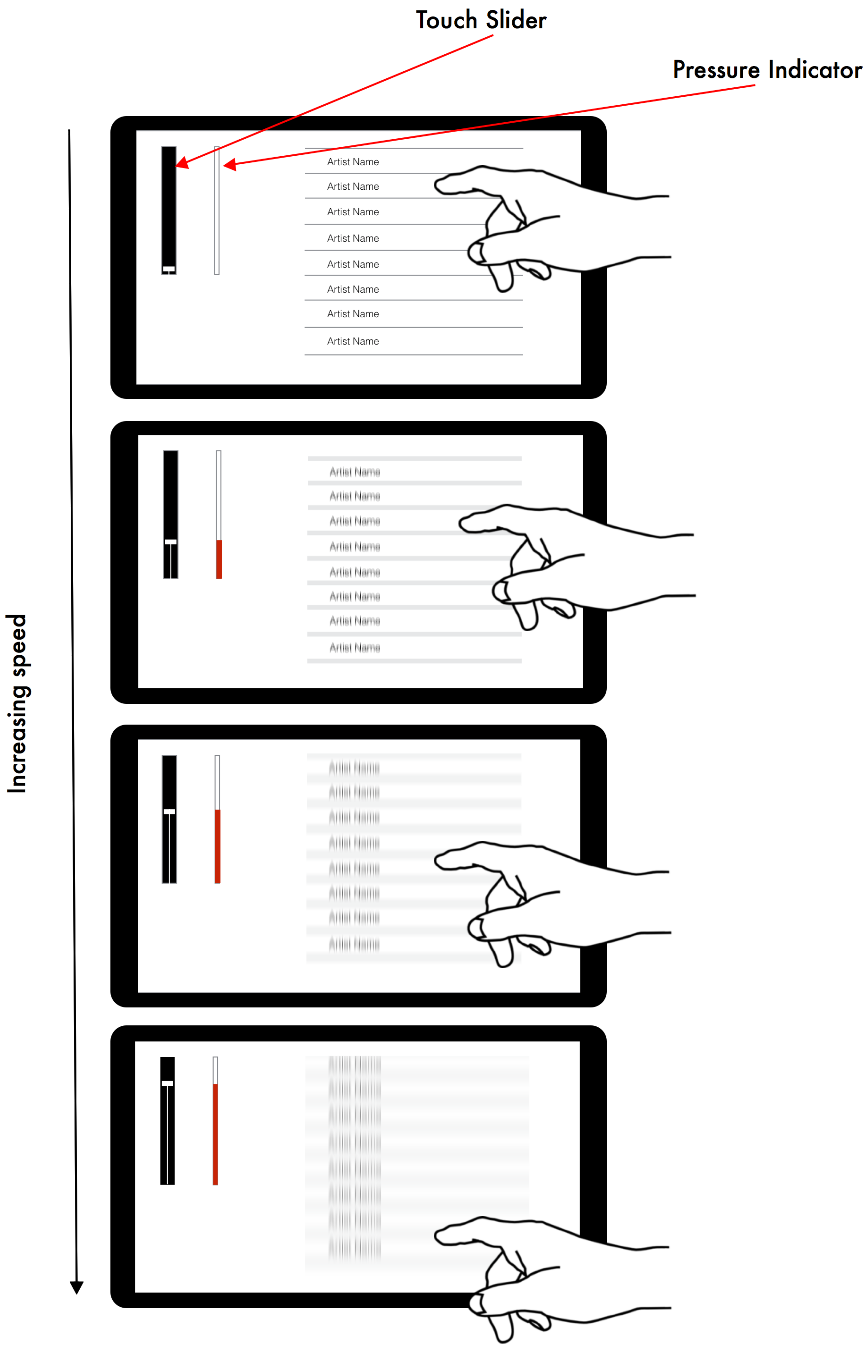


Figure 3.2: Illustration of the bimanual scrolling interaction techniques. Speed is increased by applying pressure or adjusting the touch slider. Increasing the speed increases the rate at which the viewport scrolls for each dominant hand movement.

Bimanual Techniques

An illustration of the bimanual scrolling techniques can be found in Figure 3.2. There were four bimanual techniques: Dial and Pressure, Dial and Slider, Touch and Pressure and Touch and Slider. The bimanual techniques used the same scrolling direction devices as the unimanual techniques, though two additional methods were used to control speed. The speed could be controlled dynamically using either a FSR mounted on the top left front of the device's bezel (See Figure 3.1c) or a software slider bar that appeared on the top left of the screen. Participants controlled speed using a 'pinch-grip' with their NDH via a FSR mounted on the left bezel of a tablet device. Increasing the pressure dynamically increased the speed at which the direction control methods would scroll the list. Releasing pressure from the sensor would decrease the speed. A pressure space (amount of pressure that has to be applied to reach the maximum speed) of 9 Newtons (N) was used for speed control. This was chosen because pilot tests revealed that with smaller pressure spaces, the speed control became binary, with the pinch pushing right through the pressure space. The software slider bar was also controlled by the participants' NDH. Pushing the slider bar upwards increased the speed of scrolling and *vice versa*.

In the bimanual techniques, the speed control was completely separated from the direction control and so it was no longer possible to perform 'flick' gestures on either the dial or the touchscreen to increase scrolling speed. All permutations of these bimanual techniques were used. Each if the bimanual techniques are summarised below:

Dial and Pressure This interaction technique uses the dial mounted on the rear of the device and the pressure sensor mounted on the front of the device. The dial controls the scrolling direction. By rotating the dial using the DH, the interface will scroll: clockwise down, anti clockwise up. The pressure sensor controls the scrolling speed: increasing the amount of pressure increases the speed at which the dial scrolls through the list.

Dial and Slider This interaction technique uses the dial mounted on the rear of the device and the touch slider on the left side of the touchscreen. The dial controls the scrolling direction and the touch slider controls the scrolling speed: pushing the slider up will increase the speed at which the dial scrolls through the list and *vice versa*.

Touch and Pressure This interaction technique uses the DH on the screen of the device and the pressure sensor mounted on the front of the device. The finger of the DH controls the scrolling direction - dragging up will scroll up and *vice versa* - and the pressure sensor controls the scrolling speed - increasing the amount of pressure increases the speed and *vice versa*. Doing this causes the speed at which the finger drags the interface to increase.

Touch and Slider This interaction technique uses the DH on the screen of the device and the touch slider on the right hand side of the interface. The finger of the DH controls the scrolling direction - dragging up will scroll up and *vice versa* - and the NDH controls the touch slider which controls the scrolling speed, pushing the slider up will increase the speed. Doing this causes the speed at which the interface scrolls to increase.

When a user dragged a finger from their DH across the screen or when the the dial was rotated, it was considered a translate manipulation. When the speed control modality was not engaged (when no pressure was being applied, or when the touch slider was set to zero) each translate manipulation caused the viewport to scroll 1 device-independent unit (1/96th inch per unit). The maximum speed was 10 device-independent units per translate manipulation. Increasing the scrolling speed using either Pressure or the Slider resulted in a linear increase in the number of device-independent units each translate manipulation caused the viewport to scroll. Changes in speed did not cause any change in scrolling inertia, meaning participants could not control scrolling inertia using the speed control modalities.

3.1.3 Participants

Eighteen participants (4 female, 14 male) ranging from 19-55 years of age $(M = 23)$ took part in the study, all of whom were right handed. They were paid £6 for participating.

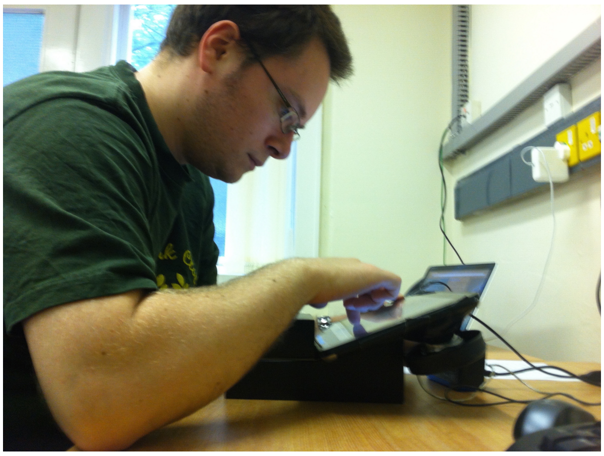
3.1.4 Hypothesis

H 1: Bimanual techniques designed with the KC Model will outperform equivalent unimanual techniques, measured by faster movement times, fewer target crossings and lower subjective workload.

H 2: The bimanual techniques will provide more benefits as the distance to the target increases, measured by faster movement times, fewer target crossings and lower subjective workload.

H 3: Within the bimanual techniques, pressure will outperform the touch slider as a speed control method, measured by faster movement times, fewer target crossings and lower subjective workload.

H 4: Within the bimanual techniques, the dial will outperform touch drag as a direction control method, measured by faster movement times, fewer target crossings and lower subjective workload.



(a)

(b)

Figure 3.3: Experimental Setup, showing a participant sat at a desk with the tablet supported on a stand.

3.1.5 Experimental Design and Procedure

The study aimed to answer two research questions. Firstly, whether the bimanual techniques were better than the unimanual ones (RQ1) and secondly which combination of bimanual modalities were most effective (RQ2). To answer the former, comparisons between each of the techniques could be made, resulting in the variable Interaction Technique with six levels: Unimanual Touch, Unimanual Dial, Bimanual Touch and Pressure, Bimanual Touch and Slider, Bimanual Dial and Pressure, Bimanual Dial and Slider. These variables were used to test H1 and H2.

However, in doing this it was not possible to say anything about the different speed and direction control modalities. Since it was not possible to compare the bimanual speed and direction controls with the unimanual techniques (the control of speed or direction could not be isolated in the unimanual techniques), an additional set of independent variables was required. Therefore, the variables *Scroll Method* and *Speed Method* were used to compare the bimanual techniques to one another, excluding the unimanual techniques. Each of these had two levels: *Scroll Method* (Touch or Dial) and *Speed Method* (Pressure or Slider). These variables were used to test H3 and H4.

Across both the research questions, the effect of *Target Distance* was considered on performance. Target distance was a useful measure as it allowed the assessment of whether having a greater control of scrolling speed was useful when moving different distances. Therefore, the independent variables in the study were Interaction Technique and Target Distance, or Scroll Method, Speed Method and Target Distance. The dependent variables were Movement Time and Number of Target Crossings. Movement Time was a measure of how long it took to complete a selection, from the first scrolling movement to the last scrolling movement before selection. Movement Time encapsulated the entire time to scroll though did not include any additional time taken to select an item (when, for instance, a participant had to move his or her hand from the dial to the touchscreen). Number of Target Crossings was defined as the number of times a target disappeared from view after being visible. This meant that how many times a participant overshot a target before selecting it could be measured, which served as a measure of control; fewer crossings meant that the technique allowed greater control. Finally, Subjective Workload was measured after each condition using the NASA TLX [Hart, S. G. & Staveland, 1988], a six item questionnaire to assess subjective workload, which gave a measure of how hard a participant thought s/he had to work using each technique.

3.1.6 Procedure

The interaction techniques were implemented on a Viewsonic Viewpad 10" touchscreen tablet running custom software on Windows 7. A Griffin Technologies PowerMate Dial, with an extended radius (using the lid from a jar of fruit so that it could be easily reached at the side of the tablet (See Figures 3.1a & 3.1b), was used for the dial conditions and a single FSR connected through a SAMH Engineering SK7-ExtGPI01 input/output module (which handled A-D conversion and sensor linearisation) was used for pressure sensing. Users applied pressure by performing a pinch gesture with the thumb and forefinger of their NDH on the left-hand bezel of the device (See Figure 3.1c).

The experimental task involved scrolling to and selecting an item from an alphabetically ordered list of 312 musical artists, which is similar to the task of selecting an artist to listen to from a long list within a music library on a tablet. In each condition, participants performed 19 tasks in total (the first 6 being training tasks). A Target Name would appear on the screen indicating the artist name that was to be selected. Target names would appear automatically on screen and after a selection had been made (whether correct or incorrect) and the next trial would begin automatically. The experimental software would return the user to the top of the list at the start of each trial. This continued until all tasks had been completed. There were 6 unique data sets used in the study to avoid learning effects, and each participant used a different data set in each condition.

The tasks were defined in terms of how far the participant would have to scroll from the very top of the list to the target. There were 13 experimental tasks (excluding the 6 training tasks) and the target to be selected in each task was different in each condition since there was a different data set for each condition. The distances associated with the tasks were 10, 35, 60, 85, 110, 135, 160, 185, 210, 235, 260, 285 and 310 items from the top. By defining the tasks in this way, and using a different dataset in each condition, we could compare the performance of each interaction technique over distance while mitigating any learning effect that might have occurred if participants were asked to select the same items in every condition. Conditions were counterbalanced using a Latin Square to mitigate any order effects. The way the user held the tablet and the amount they had to support its weight was controlled by placing the device on a docking station on a table. There were 13 tasks x 6 Interaction Techniques x 18 Participants resulting in 1404 trials.

3.2 Results: Modalities for Bimanual and Unimanual Scrolling

3.2.1 Results: Interaction Technique and Distance

This section presents an overall analysis of the bimanual and unimanual conditions in which each of the techniques are compared to each other. In doing so, it is possible to compare the performance of each technique and test H1.

Movement Time

A two-way, repeated measures ANOVA showed a main effect for Interaction Technique, $F(5, 85) = 23.555, p < .001$, a main effect for Distance, $F(12, 204) = 47.653, p < .001$. The Interaction Technique x Distance interaction was not significant, $F(60, 1020) = 1.638, p = .099$.

Post hoc pairwise comparisons with Bonferroni corrections revealed that the combination of Dial and Slider was significantly faster than all other interaction techniques ($p < .001$), Touch and Slider was significantly faster than both the Unimanual Touch and Touch and Pressure techniques ($p < .001$), Unimanual Dial was significantly faster than the Unimanual Touch ($p < .001$) and the Dial and Pressure technique was significantly faster than both the Touch and Pressure Technique ($p < .001$) and the Unimanual Touch Technique ($p < .001$) (see Figure 3.4). It generally, took participants longer to select targets that were further away, except with the 310 item Target Distance, which was faster because it could be selected simply by scrolling directly to the bottom of the list, which explains the main effect for Distance (see Figure 3.6).

Number of Target Crossings

A two-way, repeated measures ANOVA on Number of Target Crossings showed no main effect for Interaction Type, $F(5, 85) = 2.245, p = .057$. There was a main effect for Distance, $F(12, 204) = 1.516, p < .001$. There was no significant interaction.

In general, Number of Target Crossings increased with Target Distance, except with the 310 item Target Distance (see Figure 3.7), with which participants had much fewer target crossings. Since it was at the very end of the list, it was more difficult to overshoot. Though, since a Target Crossing was defined the number of times a target disappeared from view after being visible, a “crossing” was still possible if a participant scrolled to it and then navigated back up the list.

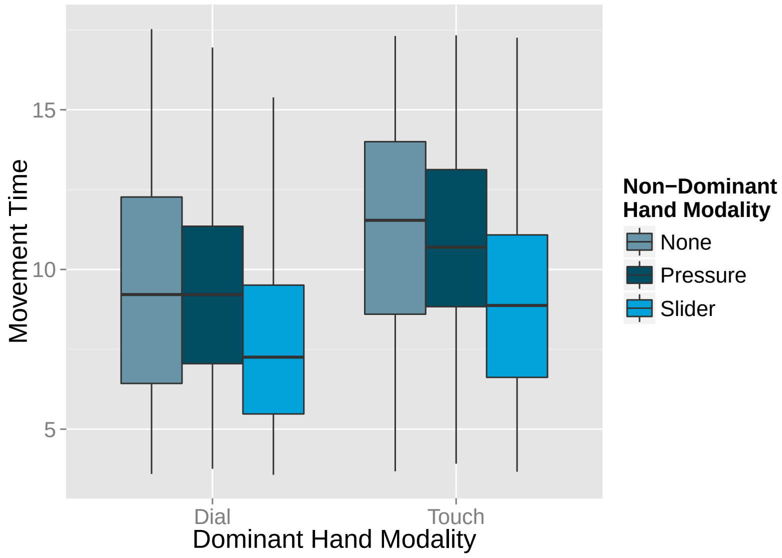


Figure 3.4: Movement Times from Experiment 1. Dial and Slider was significantly faster than all other interaction techniques $(p < .001)$**, Touch and Slider was significantly faster than both the Unimanual Touch and Touch and Pressure techniques** $(p < .001)$**, Unimanual Dial was significantly faster than the Unimanual Touch** $(p < .001)$ **and the Dial and Pressure technique was significantly faster than both the Touch and Pressure Technique** $(p < .001)$ **and the Unimanual Touch Technique** $(p < .001)$

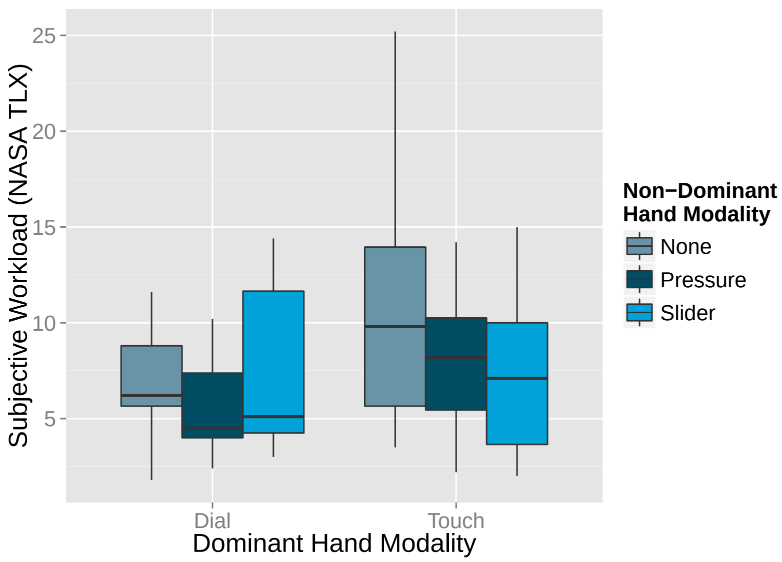


Figure 3.5: Subjective Workload (NASA TLX) scores from Experiment 1. Dial and Pressure condition had significantly lower subjective workload than the Unimanual Touch condition $(p < 0.003)$**.**

Subjective Workload

A repeated measures non-parametric Friedman test of differences was conducted on overall workload scores for each condition and was significant ($\chi^2 = 22.268, p < 0.001$, see Figure 3.5). *Post-hoc* Non-parametric Wilcoxon T tests with Bonferroni correction revealed that (adjusted $p = 0.003$) the Dial and Pressure condition had significantly lower subjective workload than the Unimanual Touch condition ($p < 0.003$). No other comparisons were significant.

Discussion

This analysis sought to determine if there were any benefits of the bimanual techniques over some equivalent unimanual techniques. The hypothesis that bimanual techniques designed to conform to the KC model would outperform equivalent unimanual techniques (H1) was generally borne out. The Dial and Slider technique was superior to the others in terms of Movement Time (see Figure 3.4) with the Dial and Pressure technique superior in terms of Subjective Workload (See Figure 3.5). These results suggest that the bimanual techniques do have advantages over unimanual equivalents.

In general, it took participants longer to select targets that were further away, which explains the main effect for Distance, but since there was no interaction effect for Interaction Technique x Distance there is no evidence to suggest that any of the bimanual techniques provide additional benefit as the distance from the target increases, and thus there is no evidence to support H2.

Since it was not possible to isolate speed control from direction control for the unimanual conditions, a fully balanced experiment was not possible. Therefore, the following section will present a more detailed analysis of the bimanual techniques to investigate the effect of each of the speed and direction control modalities on performance and attempt to explain why participants performed better with the Dial and Slider combination, though had a lower subjective workload with the Dial and Pressure combination.

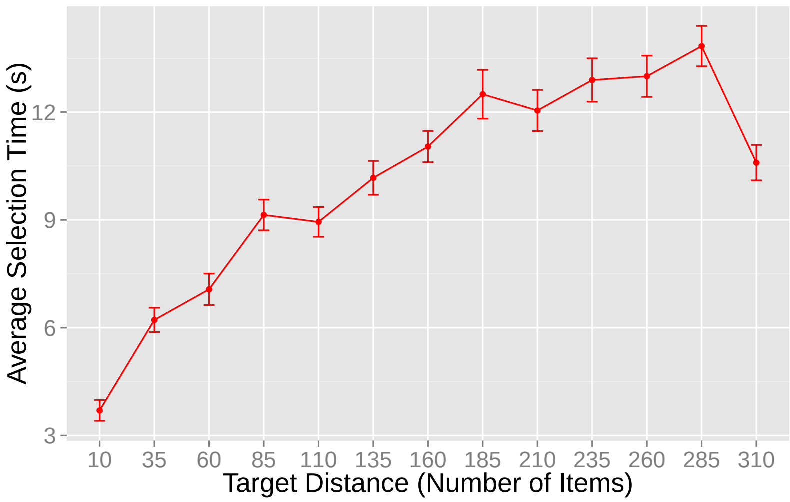


Figure 3.6: Average Selection time across Target Distance for Experiment 1. There was a significant main effect for Distance in terms of Movement Time (see Table 3.1 for *post hoc* comparison results). In general, Selection Time increased with Distance. However, for the furtherest distance (310 items) participants were faster owing to the fact that as it was close to the last item in the list.

***Post Hoc* comparisons for Movement Time**

Target Distance	10	35	60	85	110	135	160	185	210	235	260	285
10	-											
35	< 0.001	-										
60	< 0.001	1.00	-									
85	< 0.001	< 0.001	< 0.05	-								
110	< 0.001	< 0.05	.124	1.00	-							
135	< 0.001	< 0.001	< 0.001	1.00	.169	-						
160	< 0.001	< 0.001	< 0.001	< 0.05	.336	1.00	-					
185	< 0.001	< 0.001	< 0.001	.61	< 0.001	.253	1.00	-				
210	< 0.001	< 0.001	< 0.001	< 0.05	< 0.05	.678	1.00	1.00	-			
235	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.05	.554	1.00	1.00	-		
260	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.05	.600	1.00	1.00	1.00	-	
285	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.05	1.00	1.00	1.00	1.00	-
310	< 0.001	< 0.001	< 0.001	1.00	.946	1.00	1.00	1.00	1.00	.442	.053	.007

Table 3.1: *Post Hoc* comparisons for Movement Time. Target Distance represents the distance from the start of the list in number of items. Adjustment for multiple comparisons: Bonferroni. Adjusted p-values shown, where significance threshold is $p = 0.05$

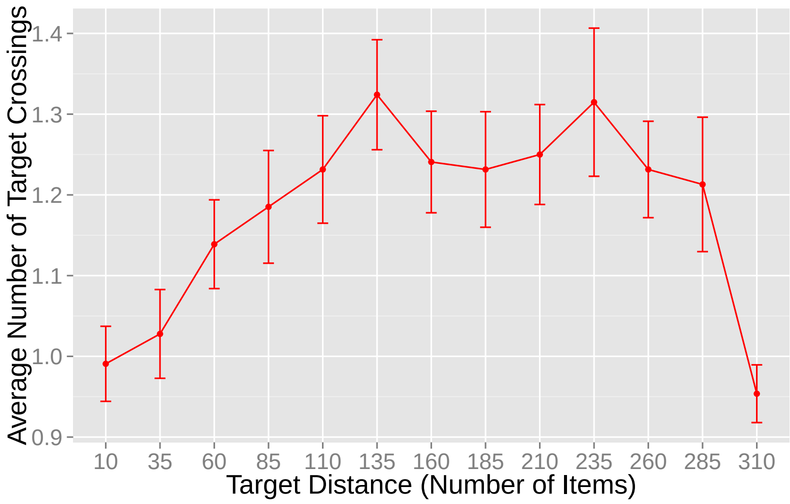


Figure 3.7: Number of Target Crossings across Target Distance for Experiment 1. There was a significant main effect for Distance in terms of Number of Target Crossings. In general, Number of Target Crossings increased with Distance (see Table 3.2 for *post hoc* comparison results). However, for the furtherest distance (310 items) participants had fewer target crossings, owing to the fact that as it was close to the last item in the list and was difficult to overshoot.

Post Hoc **comparisons for Number of Target Crossings**

Target Distance	10	35	60	85	110	135	160	185	210	235	260	285
10	-											
35	1.00	-										
60	1.00	1.00	-									
85	.638	1.00	1.00	-								
110	.161	1.00	1.00	1.00	-							
135	< 0.05	.515	1.00	1.00	1.00	-						
160	.317	.495	1.00	1.00	1.00	1.00	-					
185	.136	.903	1.00	1.00	1.00	1.00	1.00	-				
210	< 0.05	.286	1.00	1.00	1.00	1.00	1.00	1.00	-			
235	< 0.05	.280	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-		
260	.288	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-	
285	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	-
310	1.00	1.00	.368	.251	< 0.05	.056	< 0.05	.246	< 0.05	< 0.05	.105	1.00

Table 3.2: *Post Hoc* comparisons for Number of Target Crossings. Target Distance represents the distance from the start of the list in number of items. Adjustment for multiple comparisons: Bonferroni. Adjusted p-values shown, where significance threshold is $p = 0.05$

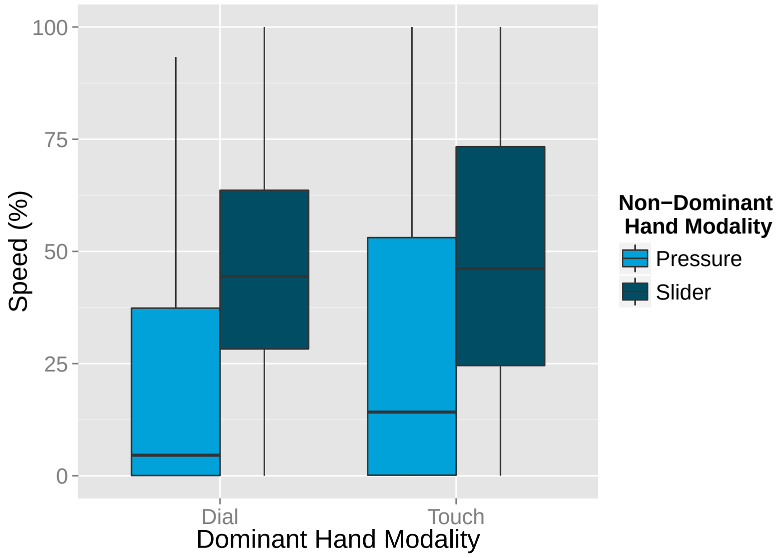


Figure 3.8: Distribution of speed in Experiment 1. The distribution of speed values was skewed toward to lower end of the scale for the techniques that used pressure for speed control and is distributed across the centre for techniques that used the on screen slider.

3.2.2 Results: Scroll Method/Speed Method

A second analysis was carried out to test H3 and H4, which are concerned with the particular modalities used within the bimanual techniques. The goal was to test which of the modalities, if any, resulted in better performance. The Independent Variables in this analysis were Scroll Method (Dial or Touch), Speed Method (Pressure or Slider) as well as Target Distance. The dependent variables were Movement Time and Number of Target Crossings.

Movement Time

A three-way, repeated measures ANOVA on the movement times showed a main effect for Scroll Method, $F(1, 17) = 44.262, p < .001$, a main effect for Speed Method, $F(1, 17) = 35.747, p < .001$ and a main effect for Distance $F(12, 204) = 27.898, p < .001$. There were no significant interactions.

In general, it took participants longer to select items that were further away in the list (see Figure 3.6). In addition, the movement times for the techniques that used the slider as a Speed Method were faster $(M = 8.330s, SD = 5.00s)$ than the techniques that used the pressure as a speed control method $(M = 10.911s, SD = 5.29s)$.

Number of Target Crossings

A three-way, repeated measures ANOVA on the number of Target Crossings showed no significant main effect for Scroll Method, $F(1, 17) = .592, p = .452$, nor for Speed Method, $F(1, 17) = .426, p = .523$. There was a the main effect for Distance $F(12, 204) = 3.381, p < .001$. Only the Scroll Method x Speed Method x Distance interaction was significant $F(12, 204) = 2.778, p < .05$.

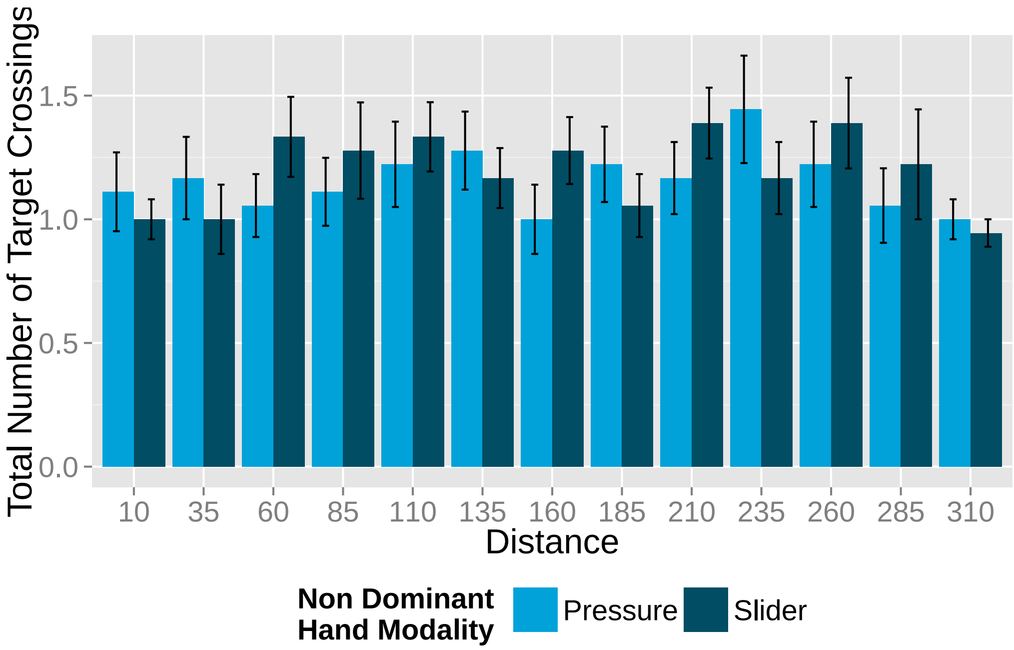
Discussion

The results from the second analysis reveal that, as a direction control method, participants performed tasks faster using the dial than with on screen touch gestures, though there was no evidence to suggest that Scroll Method has any effect on number of target crossings, lending some support to the hypothesis that participants would perform better using the dial than the touch gestures (H4). Repetitive flick and or drag gestures make it difficult to get anything but very coarse control over the scrolling speed and cause the interaction to become slow and staggered. A potential explanation for the fact that the dial turned out to be faster was because it provided more continuous control during scrolling.

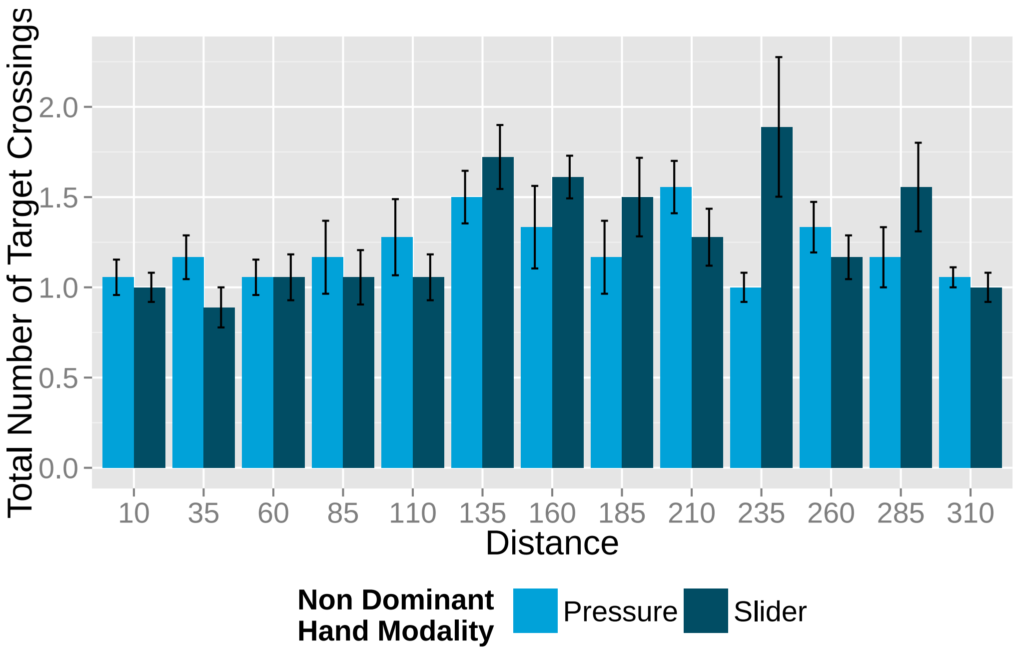
As before, it took participants longer to select targets that were further away, which explains the main effect for Distance. However, since there was no interaction effect between Scroll Method, Speed Method or Distance there is no evidence to suggest that any of the bimanual techniques provide additional benefit over any of the other techniques as the distance from the target increases in terms of movement time. As a speed control method, the touch slider was better than the pressure sensor. Participants performed tasks faster when using the touch slider than when using the pressure sensor.

There was no evidence to suggest that either of the modalities had an effect on the number of target crossings. The hypothesis that pressure would outperform the touch slider as a speed control method (H4), then, was not supported. The differences in the levels of speed achieved using each of the techniques can begin to explain these differences. Figure 3.8 shows the variation in the speed values for each technique. It can be seen that the distribution of speed values was skewed toward to lower end of the scale for the techniques that used pressure for speed control and is distributed across the centre for techniques that used the on screen slider.

During the experiment debrief, a number of participants commented that they found that they had to apply too much force in order to get to maximum speed in the pressure conditions; they therefore only applied a comfortable amount of force, and did not reach maximum speed. To scroll the list at the maximum speed, participants would have to apply a force of 9N continuously on the pressure sensor. Whereas with the touch slider it was possible to reach



(a) Target Crossings for the Touch conditions.



(b) Target Corssings for the Dial conditions.

Figure 3.9: Number of Target Crossings from Experiment 1. For the Touch Scroll Method conditions, number of target crossings remained fairly constant as distance to the target increased. However, for the Dial Scroll Method, the number of target crossings increased as distance to the target increased, and the increases were higher when the Slider Speed Control methods was used.

maximum speed by simply moving the slider knob to the top of the slider bar, participants rarely set is to the maximum value. Rather, participants commented that they only moved the slider in discrete increments or decrements because it was awkward to change. It was easier and more comfortable to travel at slower speeds with the pressure sensor, which could explain why participants took longer to complete the tasks with the pressure sensor.

As discussed above, the Dial and Slider technique was superior to the others in terms of Movement Time (see Figure 3.4) with the Dial and Pressure technique superior in terms of Subjective Workload (See Figure 3.5). The Scroll Method x Speed Method x Distance interaction was significant in terms of Target Crossings and can provide insight as to why the Dial and Pressure was subjectively preferred, while Dial and Slider resulted in objectively better performance. Figure 3.9 shows the total number of target crossings, split by both Speed Method and Scroll Method. It shows that for the Touch Scroll Method conditions, number of target crossings remained fairly constant as distance to the target increased. However, for the Dial Scroll Method, the number of target crossings increased as distance to the target increased, and the increases were higher when the Slider Speed Control methods was used. The data show that participants travelled faster while using the Slider speed control method, which would explain why the number of target crossings increased with distance: participants were more likely to speed past the targets and be unable to change the speed quickly enough to slow down (since we know they only changed the slider discretely, because it was awkward to use it to continuously vary the speed). From this, we could hypothesise that by reducing the amount of force that is required to control the pressure sensor, we could allow participants to move quickly and accurately (by giving them dynamic, continous control of the full speed capabilities) while maintaining the subjective workload benefits.

3.3 Experiment 2: Variations on the Pressure Space

The goal of the second study was to investigate further the use of pressure as a speed control method for bimanual scrolling interactions. In the previous study, the techniques that used pressure did not out-perform others, though participants perceived them to have a lower subjective workload, suggesting that it was considered easy to use. In this study, performance in a controlled linear targeting task is evaluated with smaller pressure spaces and alternative pressure mappings.

3.3.1 Interaction Techniques

There were eight interaction techniques, all of which were bimanual and all of which used pressure as a speed control method. They differed from the techniques used in the previous study in the following ways. Firstly two different, and smaller, 4N and 6N pressure spaces were used. The pressure space used in the previous study (9N) was chosen because pilot testing had suggested that too small a pressure space resulted in binary use of the speed control. Thus, while the aim of this study was to evaluate performance using smaller pressure spaces, it is not expected that the smallest pressure space will necessarily be the best.

In addition to varying the size of the pressure space, the way in which the pressure sensor controlled speed was also varied. Previously, an accelerator metaphor was used. However, participants rarely used the entire pressure space, meaning they did not always reach maximum speed. Here, the use of a 'brake' metaphor is evaluated against an accelerator metaphor. A brake metaphor could be useful as maximum speed would be the default scrolling speed, making it possible to achieve higher speeds without using the entire pressure space. Though, there is an obvious trade-off with it becoming more difficult to scroll at slower speeds, which could negatively affect targeting performance. By including this variation we hope to characterise this trade-off as well.

3.3.2 Participants

Sixteen new participants (9 female, 7 male) ranging from 19-31 years of age (M=21) took part in the study, all of whom were right handed. They were paid £6 for participating.

3.3.3 Hypothesis

H 5: The larger (6N) pressure space will outperform the smaller (4N) pressure space, measured by faster movement times, fewer target crossings and lower subjective workload.

H 6: As a method of speed control, Brake will provide better performance over longer distances than Accelerator, measured by faster movement times, fewer target over-shoots and lower subjective workload.

3.3.4 Experimental Design and Procedure

The experimental task was identical to the one in the previous study and involved participants scrolling to and selecting an item from an alphabetically ordered list of 312 musical artists. Conditions were counterbalanced using a Latin Square to mitigate any order effects.

The independent variables were: Scroll Method (Dial, Touch Drag), Pressure Space (4N, 6N), Pressure Mode (Accelerator, Brake) and Distance (10, 35, 60, 85, 110, 135, 160, 185, 210, 235, 260, 285 and 310). The dependent variables were Movement Time, Number of

Target Crossings and Subjective Workload. There were 13 tasks x 2 Scroll Methods x 2 Pressure Spaces x 2 Pressure Modes x 16 Participants resulting in 1664 trials.

3.4 Results: Variations on the Pressure Space

Movement Time

A four-way, repeated measures ANOVA on Movement Time showed a significant main effect for Scroll Method $F(1, 17) = 5.426, p < .05$ and for Distance $F(12, 204) = 11.413, p < .001$. There was no evidence that either Pressure Mode (Accelerator or Brake) or Pressure Space (4N or 6N) had any effect on Movement Time. There were no significant interactions. In general, participants took longer to scroll to targets that were further away from the start of the list and participants took longer to scroll to targets when using the Touch Scroll method $(M = 13.71s, SD = 7.13s)$ than when using the Dial Scroll method $(M = 12.43s, SD = 7.92s)$.

Number of Target Crossings

A four-way, repeated measures ANOVA on the Number of Target Crossings showed a significant main effect for Pressure Mode, $F(1, 17) = 7.583, p < .05$, and a significant main effect for Distance $F(12, 204) = 2.985, p < .001$ as well as a significant interaction effect for Mode x Distance $F(12, 204) = 1.973, p < .05$ and for Scroll Method x Pressure Space x Pressure Mode x Distance $F(12, 204) = 2.246, p < .05$.

In general, there were significantly more target crossings in the conditions in which the pressure sensor was used as a brake $(M = 1.35, SD = 0.9)$ than in the conditions in which it was used as an accelerator $(M = 1.21, SD = 0.58)$. *Post hoc* pairwise comparisons of the number of target crossings across all 13 Distances revealed that when selecting the target at position 310 (the distance furthest away from the top, which was on the last page of targets and could not be overshot) participants had significantly fewer target crossings than with any of the other distances $(p < .001)$. As can be seen in Figure 3.10, the Pressure Mode x Distance interaction can be explained by the fact that for the targets closer to the start of the list, the Brake mode had a much larger number of target crossings than the Accelerator mode, though as the target distance increases, the difference between the two modes decreases.

Subjective Workload

Non-parametric Wilcoxon T tests failed to show significance between workload scores for either Scroll Method $(p = 0.297)$, Pressure Space $(p = 0.175)$ or Pressure Mode $(p =$

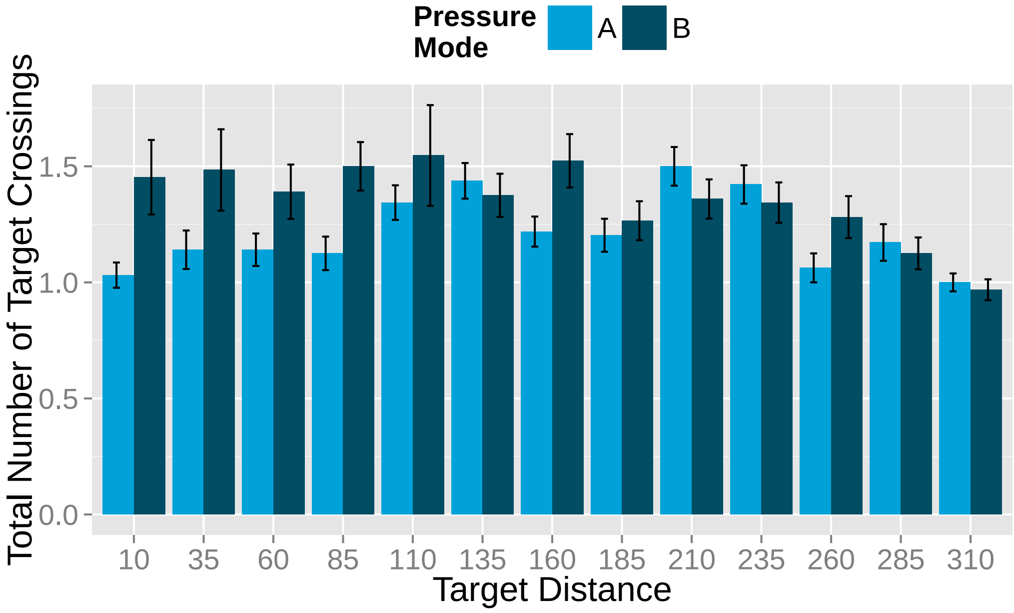


Figure 3.10: Number of Target Crossings from Experiment 2. There were significantly more target crossings in the conditions in which the pressure sensor was used as a brake $(M = 1.35, SD = 0.9)$ **than in the conditions in which it was used as an accelerator** $(M = 1.21, SD = 0.58)$**. The Pressure Mode x Distance interaction can be explained by the fact that for the targets closer to the start of the list, the Brake mode had a much larger number of target crossings than the Accelerator mode, though as the target distance increases, the difference between the two modes decreases.**

$0.129)$.

3.4.1 Discussion

The results of the second experiment did not show a clear advantage of one Pressure Space over another, but did show an advantage for the Accelerator Pressure Mode over Brake. There was no evidence to suggest that the differences in Pressure Space (4N or 6N) or Pressure mode (Accelerator or Brake) had any effect on Movement time, though participants had significantly more target crossings when using Brake (especially for targets that were closer to the start of the list). The data do suggest that participants could perform faster with the Dial over Touch as a method to control scrolling direction, supporting H4. This mirrors the results obtained in the first study and suggests that the dial is better suited as a direction control device for these interactions.

Brake mode resulted in less accurate performance for targets that were closer to the start position. Since, by definition, the Brake mode moves very quickly for small movements when no pressure is applied, and the starting state for the condition was to have no pressure applied, then for targets that are a short distance away participants are more likely to overshoot. The potential advantage of the Brake mode lies in the fact that it requires less effort to achieve higher speeds, though it comes with the trade-off of more effort to reach lower speeds.

Thus, it is not clear whether this potential advantage has any merit in realistic situations due to the extra effort involved in travelling short distances. In addition, there was no evidence that the Brake mode actually improved performance or reduced subjective workload for larger distances, leading to the rejection of H6. When using the Accelerator mode, people can always navigate to a target, albeit slowly, without needing to apply a great deal of pressure, which for short distances seems to result in more accurate performance.

3.5 General Discussion

3.5.1 Dial vs. Touch for Direction Control

With the prevalence of touchscreens, physical dials are not particularly common on modern devices. However, the results in this chapter suggest that, in terms of movement time and subjective workload, they are superior to flick and drag gestures on a touchscreen for the control of scrolling direction. Numerous keyboards and mice contain small dials that are used for scrolling through content on a desktop machine, and several Apple iPod devices featured a front mounted touch sensitive dial that was the main source of input.

A dial provides the opportunity for continuous control during a scrolling task, unlike the flick and drag gestures that are used on touchscreen devices, which may be part of an explanation as to why it performed better in the studies described. However, the dial used in this study was cumbersome when mounted on the device. In the next chapter, less obtrusive ways to incorporate a dial into the form factor of a tablet, such as with a flat touch sensitive device, will be investigated.

3.5.2 Non-Dominant Hand Modalities

In terms of speed control methods, the evidence suggests that the touch slider resulted in faster performance than the pressure sensor, though participants favoured the dial and pressure sensor technique in terms of subjective workload, implying they found it easier to use. In Experiment 1, the number of target crossings provided insight as to why the Dial and Pressure was subjectively preferred, while Dial and Slider resulted in objectively better performance: as target distance increased, the number of target crossings observed was higher when using the touch slider than when using the pressure sensor. While participants were able to get to the target faster using the slider method, over long distances they were more

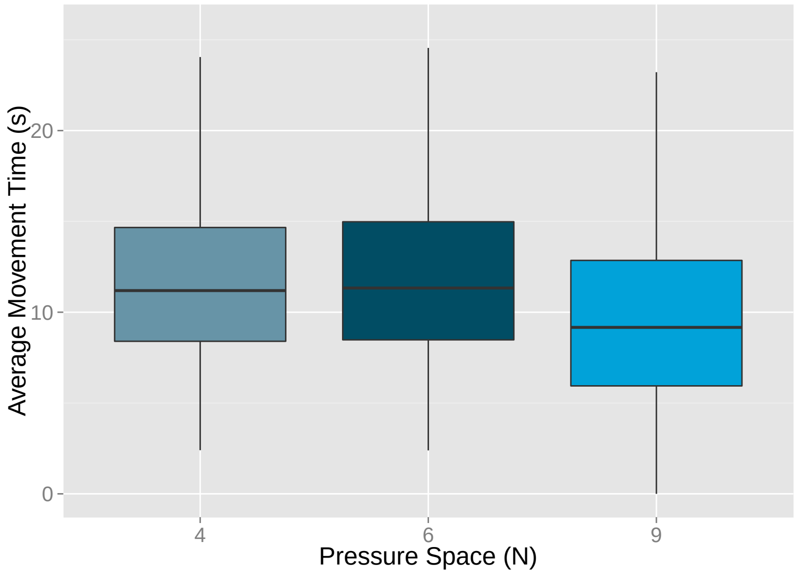


Figure 3.11: Overall Selection Time for each Pressure Space. 4N and 6N Pressure Space from Experiment 2. 9N Pressure Space from Experiment 1.

likely to overshoot than with the pressure sensor. It is possible that since the touch slider does not afford continous dynamic control over the scrolling speed and as participants travelled faster while using the slider speed control method, it was difficult to control, which resulted in higher subjective workload ratings.

Pressure Spaces

There were three 'pressure spaces' used across the studies presented in this chapter: 9N in the first study and 4N and 6N in the second. It was observed that the 9N pressure space might have been too large for participants to comfortably apply the continous force required to reach the maximum speed.

In response to this, the second study contained two smaller pressure spaces (4N and 6N) as well as introducing a 'brake' metaphor for speed control (alongside the 'accelerator' metaphor that was used in the first study) in an attempt to make it more comfortable to control the scrolling at higher speeds. It was hypothesised that the 6N pressure space would give rise to better performance than the 4N pressure space since it would reduce the amount of force participants had to apply, while still giving a wide enough range to allow expressive use of the speed control. However, there was no evidence to suggest that the differences in pressure space had any effect on performance. It is possible that the distances travelled during the experiment were too small to allow for truly expressive use of the speed control. For some target distances, it may not have been possible to achieve maximum speed before the target was reached (or overshot). If this were the case, the effect of pressure space would be masked because the task did not require it to be fully utilised. Figure 3.11 shows selection times for each pressure space used across both experiments. Only data from the Accelerator conditions from Experiment 2 is shown, since there was no Brake condition in Experiment 1. Selection times for the larger 9N pressure space are still generally faster than those for the smaller 4N and 6N pressure spaces. Although it is not possible to make a formal comparison across experiments, it does suggest that there is something we do not understand about the use of pressure on tablet devices and that perhaps the expressive range afforded by the larger space could be beneficial in some way, despite the fact that participants did not use make use of the full range. The following chapter will explore this issue by evaluating the interaction techniques using an image browsing task that was longer and more involved than the targeting task evaluated here. The use of the techniques can be studied when the user has to navigate a collection in more detail, thus giving more opportunity to make use of the input strategies available.

3.5.3 Limitations

There are a number of limitations with the studies presented in this chapter. Firstly, during the studies participants were not required to hold and support the weight of the tablet device – the device was propped up on a docking station, placed on a table – meaning that the effect of holding the device in the NDH while also interacting using the auxiliary input modality (in this case touch slider or pressure) is still unknown. In these studies, participants' NDH was not encumbered by holding the device and participants were free to position their NDH in any way. In the remaining chapters, the experimental design involves participants sitting on a chair holding the device using their NDH, while supporting the weight of the device on their lap in order to evaluate performance in a more realistic context.

Secondly, the technologies used to implement the Unimanual Touch technique were not the refined and modern implementations of touchscreen intertial scrolling that have now become common. The implementation used the default intertial scrolling from the Windows 7 Surface 2.0 SDK, running on a 10" Viewsonic Viewpad. It is difficult to quantitatively contrast and compare implementations of inertial scrolling across devices and SDKs. However, considering that at the time of the experiment, versions of the Apple iPad and various Android tablet devices were more common than touchscreen tablets running Windows 7, and since Windows 7 was not an operating system designed to natively support touch input, it would be naive to generalise the results from this study to all devices that support unimanual touchscreen scrolling. In the next chapter, an Asus Transformer Prime, running Android 4.1.1 will be used to evaluate the same techniques, using a different task.

3.6 Conclusions

Research Question 1 asked:

> *Can bimanual input techniques improve scrolling performance on tablet devices?*

The studies presented here suggest that the bimanual scrolling techniques are better than the *status quo* unimanual techniques in terms of both performance and preference, lending support to the body of evidence in HCI that the KC Model [Guiard, 1987] is a useful tool to inform the design of bimanual interactions that allow people to carry out tasks more effectively than with unimanual equivalents. The studies also suggest that, as a method of scrolling control, the physical dial is better than conventional touchscreen gestures in both the bimanual and unimanual techniques. However, these results are tentative and subject to the limitations outlined above and will be addressed in the next chapter.

Research Question 2 asked:

> *Can novel input modalities (such as pressure) improve performance for bimanual tablet based scrolling interactions?*

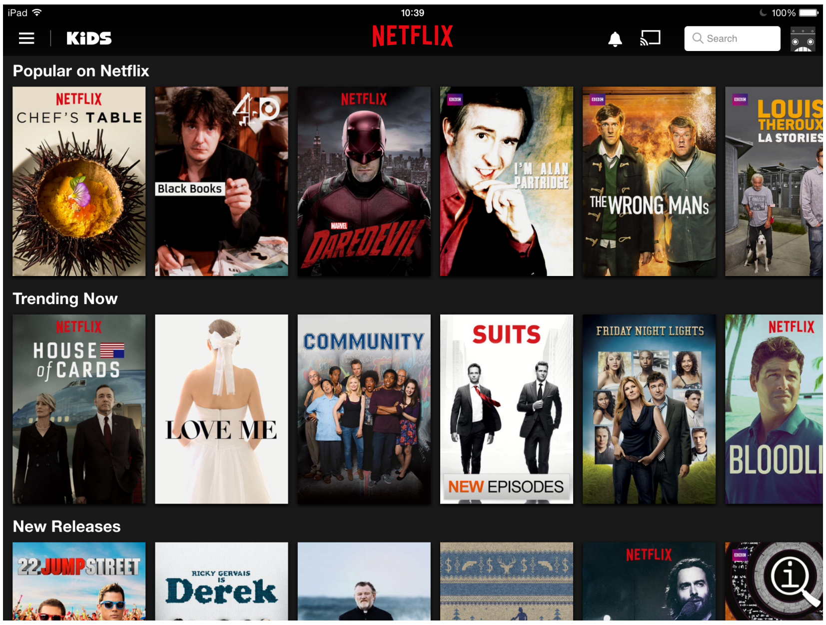
The studies presented in this chapter suggest that splitting the control of scrolling speed and scrolling direction across two hands is a viable way to scroll on a tablet, which could support simultaneous two-handed input while the user is holding the device. However, it is currently unclear whether pressure is a viable modality for providing effective auxiliary input for bimanual interaction techniques on touchscreen tablet devices.

Chapter 4

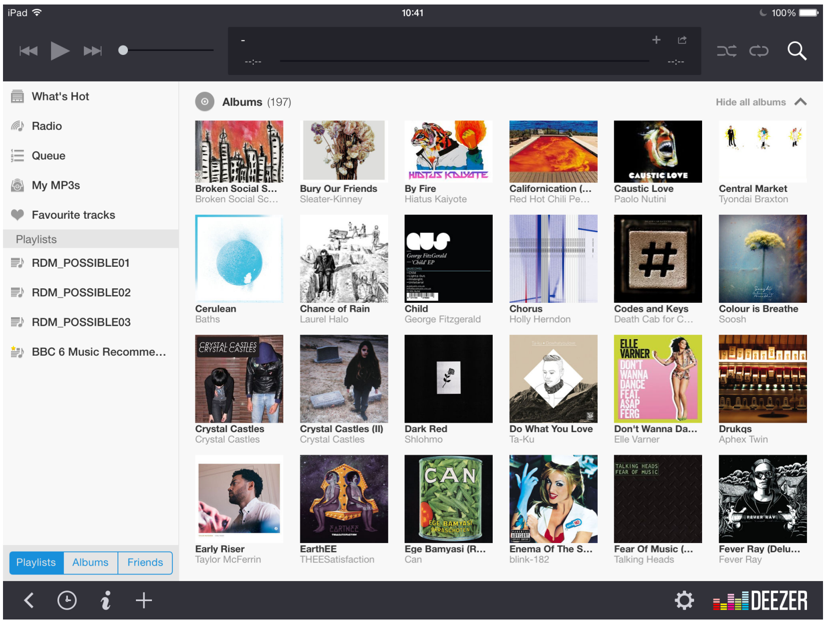
Browsing Media Collections

It is not uncommon for personal and streaming based media collections to contain thousands, if not hundreds of thousands of items, access to which is often provided by scrolling though grids of images that represent each item (see Figure 4.1). While the need for browsing through large collections can be mitigated providing good recommendations or by improving search, there is always a need to have an efficient and appealing way to access 'your stuff' in its entirety. Cunningham *et al.* [Cunningham *et al.*, 2004] note that browsing through personal music collections may essentially be an undirected linear search until something strikes the user as what he or she wants to hear at that moment; suggesting that browsing through entire collections is a valuable task to support serendipitous discoveries when no particular target is in mind.

In the previous chapter, a number of bimanual scrolling techniques were evaluated to establish whether they were better than current one-handed techniques, when selecting targets from long lists. In general, the bimanual techniques showed advantages over standard one-handed scrolling techniques in terms of both performance and preference. A linear targeting task in which participants navigated to and selected targets from an alphabetically ordered list of musical artists was used to evaluated the techniques. While this was a good representation of how people scroll to *known* targets in long lists, it was not particularly realistic in terms of how people browse their music collections when they are unsure about what they are looking for. In this chapter, a more realistic image browsing task is used to evaluated the same techniques to determine whether the results hold.



(a) Netflix



(b) Deezer

Figure 4.1: Personal and streaming based media collections – such as Netflix for films (a) and Deezer for music (b) – often contain thousands, if not hundreds of thousands of items, access to which is often provided by scrolling though grids of images that represent each item.

4.1 Experiment 3: Image Browsing

This study was based on the premise that the control of scrolling speed and vertical scrolling direction can be thought of as separate tasks and that the current *status quo* of combining both into a single unimanual gesture on a touchscreen or on physical dial can be improved upon. The experiment sought to determine whether splitting the control of scrolling speed and scrolling direction over two hands, in accordance with the KC Model [Guiard, 1987], could improve user performance in a one-dimensional scrolling task on a touchscreen tablet device.

4.1.1 Input Methods

The interaction techniques were the same as those used in the previous chapter. For speed control, a pressure sensor and an onscreen touch slider were used, and for direction control conventional touchscreen drag gestures and a rear mounted dial were used. However, in this chapter a flat, capacitive circular touch surface – similar to the circular touch control found on the front of an iPod Classic or the Beosound Moment (see Figure 4.2) – is used as a dial. The dial was mounted on the back of the device (see Figure 4.4) so as to allow the user to interact with it without changing the device's form factor or blocking screen real estate; while also allowing them to simultaneously hold and interact with the device. In the context of touchscreen tablet use, this is a more realistic hardware configuration than the rear mounted physical dial used in the previous chapter. An overview of each interaction techniques is given below:

Touch This interaction technique requires the DH only. It operates like other touchscreen scrolling mechanisms - using flick and drag gestures on the screen. Dragging a finger on the screen will scroll in the direction that the finger is dragged - flicking on the screen will cause the content to scroll faster.

Dial This interaction technique requires the DH only and uses the capacitive dial mounted on the rear of the device (See Figure 4.4). Rotating the dial caused the interface to scroll - clockwise down, anti clockwise up. By performing flicks using the dial, the interface will scroll faster - much in the same way as it does for normal touchscreen scrolling.

Dial and Pressure This interaction technique uses the capacitive dial mounted on the rear of the device and the pressure sensor mounted on the front of the device. The dial controls the scrolling direction – by rotating the dial using the DH, the interface will scroll

(a) iPod Classic (b) Bang & Olufsen Beosound Moment

Figure 4.2: Devices with a flat, capacitive circular touch input surface.

– clockwise down, anti clockwise up – and the NDH controls the scrolling speed using a pressure sensor – increasing the amount of pressure increases the speed at which the dial scrolls through the list.

Dial and Slider This interaction technique uses the capacitive dial mounted on the rear of the device and the touch slider on the left side of the touchscreen. The dial controls the scrolling direction and the touch slider controls the scrolling speed – pushing the slider up will increase the speed at which the dial scrolls through the list and *vice versa*.

Touch and Pressure This interaction technique uses the DH on the screen of the device and the pressure sensor mounted on the front of the device. The finger of the DH controls the scrolling direction – dragging up will scroll up and *vice versa* – and the pressure sensor controls the scrolling speed – increasing the amount of pressure increases the speed and *vice versa*. Doing this causes the speed at which the finger drags the interface to increase.

Touch and Slider This interaction technique uses the DH on the screen of the device and the touch slider on the right hand side of the interface. The finger of the DH controls the scrolling direction - dragging up will scroll up and *vice versa* – and the NDH controls the touch slider which controls the scrolling speed, pushing the slider up will increase the speed. Doing this causes the speed at which the finger drags the interface to increase.

4.1.2 Participants

Twelve participants (7 male, 5 female), aged between 18-32 ($M = 21, SD = 3.5$), all right-handed, took part, over two sessions separated by a week. The study took about an hour to complete in each session. Participants were paid £12 on completion of both sessions.

Figure 4.3: Example images from CLEF 2007 medium/visual category.“Night shots of cathedral” (left) and “Birds Flying” (right)

4.1.3 Experimental Design and Procedure

An image browsing task similar to the task of scrolling through and selecting an item from large media collections, such as the “album” browsing screen on Deezer or the movie browsing interface on Netflix (see Figures 4.1a and 4.1b) was used. The task was chosen to resemble the way people browse through media collections using visual cues without necessarily having a particular target in mind [Cunningham *et al.*, 2004].

Participants were asked to scroll through a collection of images, highlighting relevant images as they go. They were presented with 320 images in a random order, given a description of a class of images (such as Night shots of cathedral, see Figure 4.3) and were asked to navigate through the collection and mark images they considered relevant. The ImageCLEF 2007 image collection was used [Deselaers *et al.*, 2008]. ImageCLEF 2007 is a set of 20,000 images, 60 search topics and associated relevant judgements. The topics are categorised into a number of different categories such as easy/medium/hard, semantic/visual. Six task were chosen from the medium and visual categories. For each task, 20 relevant and 300 irrelevant images were selected. Subjects were not told the proportion relevant to irrelevant images in the collection and were given no indication of whether an image they had selected was relevant or not. They had to rely solely on their judgement of the images with no feedback.

There was a time limit of 2.5 minutes for each task. This time limit was chosen because pilot runs of the study suggested that it was long enough for completion of the task. Tasks were counterbalanced using a latin square and participants carried out the task twice (using the same images) in the same session. Participants were told that there was a time limit of 2.5 minutes on each task and were told that once the time limit was reached, task would end automatically and a message to that effect would be displayed on the screen. There was no indication of the time remaining displayed on the screen.

The study aimed to answer two research questions. Firstly, whether the bimanual techniques

Figure 4.4: Experimental Hardware. The pressure sensor and the touch slider can be seen on the image on the left, at the top left of the touchscreen and bezel, respectively. The image on the right shows the back of the device, and the flat capacitive circular touch surface.

were better than the unimanual ones. To do this, each of the techniques were compared directly, resulting in the variable Interaction Technique with six levels: Unimanual Touch, Unimanual Dial, Bimanual Touch and Pressure, Bimanual Touch and Slider, Bimanual Dial and Pressure, Bimanual Dial and Slider.

However, as with the previous chapter, it is not possible to say anything about the different speed and direction control modalities that are being used. Since it is not possible to compare the bimanual speed and direction controls with the unimanual techniques (the control of speed or direction cannot be isolated in the unimanual techniques), an additional set of independent variables was required. Therefore, the variables Scroll Method and Speed Method were used to compare the bimanual techniques to one another, excluding the unimanual techniques. Each of these had two levels: Scroll Method (Touch or Dial) and Speed Method (Pressure or Slider).

Across both the research questions, the effect of iteration was considered. Iteration was a useful measure as it enabled the assessment of whether being more familiar with the collection (as may be the case in a real life media browsing task) the second time had an effect on performance. Therefore, the independent variables in the study were Interaction Technique and Iteration, or Scroll Method, Speed Method and Iteration. The dependent variables were Precision and Recall. After each condition, subjective workload was assessed with NASA TLX [Hart, S. G. & Staveland, 1988]. Precision was a measure of how accurate the selections participants made were (i.e. what proportion of images selected were relevant). Recall was a measure of what proportion of relevant images were selected overall.

The interaction techniques were implemented on an Asus Transformer Prime 10 touchscreen tablet running custom software on Android (4.1.1). A Phidgets Circular Touch sensor was mounted on the rear of the device that was used for Dial input and an Android IOIO board and a single force-sensing resistor, with a pressure space of $9N$, were used for pressure sensing (See Figure 4.4). Users applied pressure by performing a pinch gesture with the thumb and forefinger of their NDH on the left-hand bezel of the device. Participants were instructed to support the tablet with their NDH as it rested on their lap with the devices tilted towards their face. In total there were 12 Participants x 6 Interaction Techniques x 2 Iterations = 144 Trials.

4.1.4 Hypothesis

H 1: Bimanual techniques designed with the KC Model will outperform equivalent unimanual techniques, measured by higher precision, higher recall and lower subjective workload;

H 2: Within the bimanual techniques, pressure will outperform the touch slider as a speed control method, measured by higher precision, higher recall and lower subjective workload;

H 3: Within the bimanual techniques, the dial will outperform touch drag as a direction control method, measured by higher precision, higher recall and lower subjective workload.

4.2 Results: Experiment 3

4.2.1 Interaction Technique x Iteration

Precision

A two-way repeated measures ANOVA on precision showed a main effect for Interaction Technique, $F(5,55) = 4.068, p < 0.01$. There was no main effect for Iteration, $F(1,11) = 4.263, p = .066$ and the Interaction Technique x Iteration interaction was not significant, $F(5,55) = 1.748, p = .180$.

Figure 4.5 gives an overview of the Precision results from Experiment 3. *Post hoc* pairwise comparisons with Bonferroni correction revealed that the Unimanual Dial conditions had significantly lower precision than the Bimanual Dial and Pressure conditions ($p < 0.05$). No other comparisons were significant.

Recall

A two-way repeated measures ANOVA on recall showed a main effect for Interaction Technique, $F(5,55) = 3.16, p < 0.05$. There was no main effect for Iteration, $F(1,11) =$

$4.263, p = .066$ and no interaction between Interaction Technique and Iteration, $F(5, 55) = 1.748, p = .141$.

Figure 4.6 gives an overview of the Recall results from Experiment 3. *Post hoc* pairwise comparisons with Bonferroni correction revealed that the Dial and Slider condition had significantly lower recall than the Touch and Pressure condition ($p < 0.05$), Touch and Slider ($p < 0.05$) and Dial and Pressure ($p < 0.001$) conditions.

Subjective Workload

Figure 4.7 gives an overview of the Subjective Workload results from Experiment 3. A repeated measures non-parametric Friedman test of differences was conducted on overall workload scores for each condition and was significant ($\chi^2 = 18.0476, p < 0.05$). *Post hoc* non-parametric Wilcoxon T tests with Bonferroni correction (corrected $p = 0.003$) revealed that Unimanual Dial condition had significantly higher subjective workload than the Bimanual Dial and Touch ($p < 0.003$) and Unimanual Touch ($p < 0.003$) conditions.

Discussion

The Unimanual Dial condition did not perform well. It had the lowest precision and recall scores for any of the techniques evaluated (significantly lower in terms of precision), and highest subjective workload. In post experimental debrief sessions participants commented that they did not like the “flick” functionality in the Unimanual Dial conditions as they found it difficult to control. Ergonomically, the flick functionality differed from the equivalent functionality of the dial evaluated in the previous chapter. This time, flicks were performed on a flat surface on the back of the device (instead of on a curved surface, on the side of the device), which clearly did not afford the same levels of performance (Unimanual Dial was significantly faster than the Unimanual Touch technique in the first experiment of the previous chapter). Further, the Dial and Slider technique had significantly lower recall than Touch and Pressure, Touch and Slider and Dial and Pressure, leading to the conclusion that a rear mounted, flat capacitive dial is not a particularly good modality for flicking though collections of images on its own, or as a direction control as part of a bimanual technique.

In general, the bimanual techniques outperformed the unimanual dial technique, lending some support to H1. However, there was no evidence that any of the bimanual techniques provided benefit over Unimanual touch.

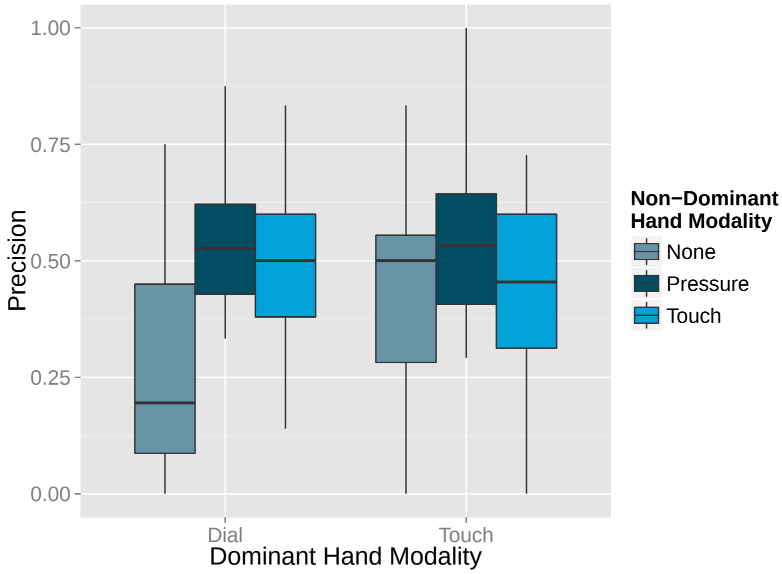


Figure 4.5: Precision by Interaction Technique from Experiment 3. The Unimanual Dial conditions had significantly lower precision than the Bimanual Dial and Pressure conditions $(p < 0.05)$**.**

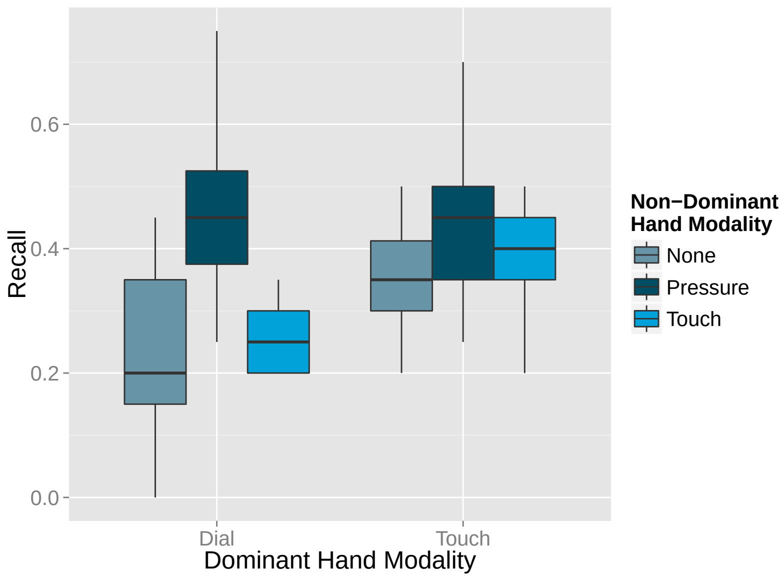


Figure 4.6: Recall by Interaction Technique from Experiment 3. The Dial and Slider condition had significantly lower recall than the Touch and Pressure condition $(p < 0.05)$**, Touch and Slider** $(p < 0.05)$ **and Dial and Pressure** $(p < 0.001)$ **conditions.**

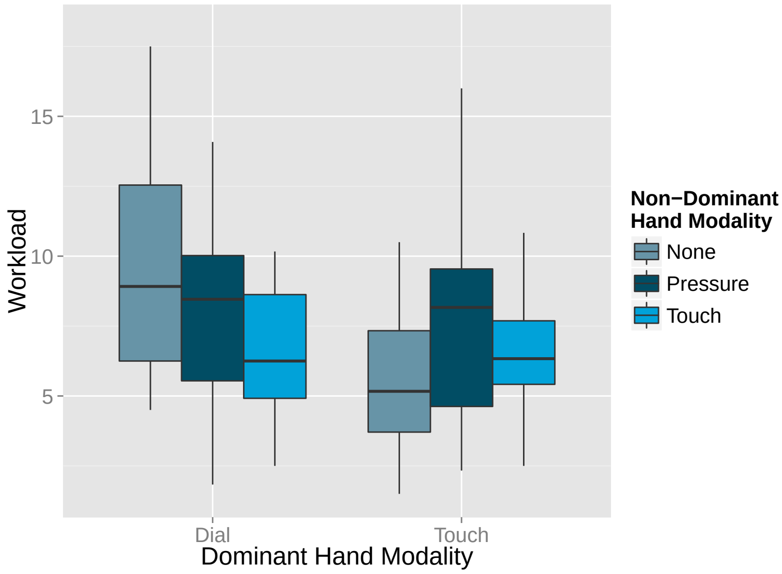


Figure 4.7: Subjective Workload (NASA TLX) from Experiment 3. Unimanual Dial condition had significantly higher subjective workload than the Bimanual Dial and Touch ($p < 0.003$) and Unimanual Touch ($p < 0.003$) conditions.

4.2.2 Speed Mode x Scroll Mode x Iteration

Precision

A three-way repeated measures ANOVA on precision showed a significant main effect for Iteration, $F(1, 11) = 6.205, p < 0.05$. The main effect for Scroll Mode was not significant $F(1, 11) = 0.636, p = 0.444$ nor was the main effect for Speed Mode $F(1, 11) = 3.302, p = 0.099$. There were no significant interactions. Precision was higher in the second iteration $(M = .548)$ than in the first iteration $(M = .492)$.

Recall

A three-way repeated measures ANOVA on recall revealed a main effect for Speed Mode, $F(1, 11) = 37.148, p < 0.001$. There was no main effect for Scroll Mode, $F(1, 11) = 4.234, p = 0.67$ or Iteration, $F(1, 11) = 0.039, p = 0.848$. The Scroll Mode x Speed Mode interaction was significant, $F(1, 11) = 6.831, p < 0.05$ as was the Speed Mode x Iteration interaction, $F(1, 11) = 5.944, p < 0.05$. The Scroll Mode x Iteration interaction was not significant, $F(1, 11) = 3.176, p = .105$ nor was the Scroll Mode x Speed Mode x Iteration interaction $F(1, 11) = 1.185, p = .302$.

Generally, the techniques that used Pressure had a higher average recall $(M = 0.46)$ than those that used the Slider $(M = 0.32)$, which explains the main effect for Speed Mode. The

Scroll Mode x Speed Mode interaction can be explained by the fact that the techniques that used Pressure had a higher recall, there no significant difference in recall between the Dial + Pressure and the Touch and Pressure conditions whereas the Dial and Slider technique performed significantly worse than each of the other bimanual techniques. As was reported above, pairwise comparisons of each of those techniques revealed that the Dial and Slider combination had significantly lower recall. The Speed Mode x Iteration interaction can be explained by the fact that the Pressure had a higher level of Recall than Slider overall, though the performance decreased slightly with pressure during the second iteration, while it increased slightly with the Slider.

4.2.3 Discussion

In terms of both Precision and Recall, the Dial and Pressure condition was significantly better than the Dial condition, which suggests that using a pressure sensor to control the speed in a dial based scrolling interaction is superior to adding scrolling speed control into the dial as “flick” gestures. This is relevant as it means the way speed control is implemented in some commercially available devices (such as the BeoSound 5), where the speed control is incorporated into a physical dial, is not a suitable solution for similar sized flat capacitive dials. In this case, adding speed control though the use of pressure may be a better solution.

In terms of Recall, Pressure was a better speed control method than the Slider; pressure was consistently good across both direction control modalities, while the touch slider was significantly worse than the others when used with a dial. This is relevant to this work in so far as it suggests that pressure is beneficial as an auxiliary modality with different combinations of primary input modality. However, from the results of this study, there is no evidence to suggest that the pressure sensor as part of a bimanual interaction provides any benefit over the Unimanual Touch condition.

4.3 Experiment 4: Image Browsing Follow Up

The study presented in the previous section yielded some useful insights into the relative merits of each of the modalities that constituted the bimanual interaction techniques; however, the results give little insight on whether they are more or less effective than current touchscreen scrolling techniques. If the bimanual techniques do not provide concrete benefit over current one-handed techniques then, regardless of the relative merits of each modality within them, it is unlikely that they will be of use in a realistic setting.

The time limit imposed on the task was designed to push participants into trying to finish the task as quickly as possible with the goal of highlighting efficiency benefits of the techniques used. Though, in a realistic context such a time constraint does not necessarily exist, especially in a media browsing task. Therefore, a follow up study was designed to probe the relative merits of the techniques where time was not a constraint on performance. In this study, carried out a week after the first study, the same participants performed the same task, though with a longer time limit of 7.5 minutes in which to complete it. If participants found all relevant images within that time limit, the task would end. This new time constraint was tested in initial pilot studies and was deemed sufficiently long for participants to traverse the collections comfortably several times so as to test whether the best performing bimanual techniques from the previous study could provide a benefit over normal touchscreen scrolling techniques in a controlled browsing task.

The previous study found pressure to be the better speed control modality and one that performed consistently well independent of scrolling method. Therefore, in this study both of the bimanual scrolling techniques with pressure were used: Dial + Pressure and Touch + Pressure.The Unimanual Touch technique was also included to provide a comparison. The experimental design and procedure was the same as before, except new image collections were used. They conformed to the medium/visual criteria as before. Eleven of the 12 participants that took part in the previous study returned for this study, therefore all participants were familiar with the techniques and task. In total there were 11 Participants x 3 Interaction Techniques x 2 Iterations = 66 Trials.

4.4 Results: Experiment 4

4.4.1 Precision

Figure 4.8 gives an overview of the Precision results from Experiment 4. A two-way repeated measures ANOVA on precision showed no main effect for Interaction Technique, $F(2, 20) = .299, p = .745$, no main effect for Iteration, $F(1, 10) = .163, p = .695$ and no interaction between the two, $F(2, 20) = 2.138, p = .144$ (see Figure 4.8).

4.4.2 Recall

Figure 4.9 gives an overview of the Recall results from Experiment 4. A two-way repeated measures ANOVA on recall showed no main effect for Interaction Technique, $F(2, 20) = .427, p = .658$, a significant main effect for Iteration, $F(1, 10) = 10.862, p < 0.05$ and no significant interaction between the two, $F(2, 20) = .676, p = .520$. Recall was significantly higher in the second iteration $(M = 0.37)$ than in the first $(M = 0.37)$.

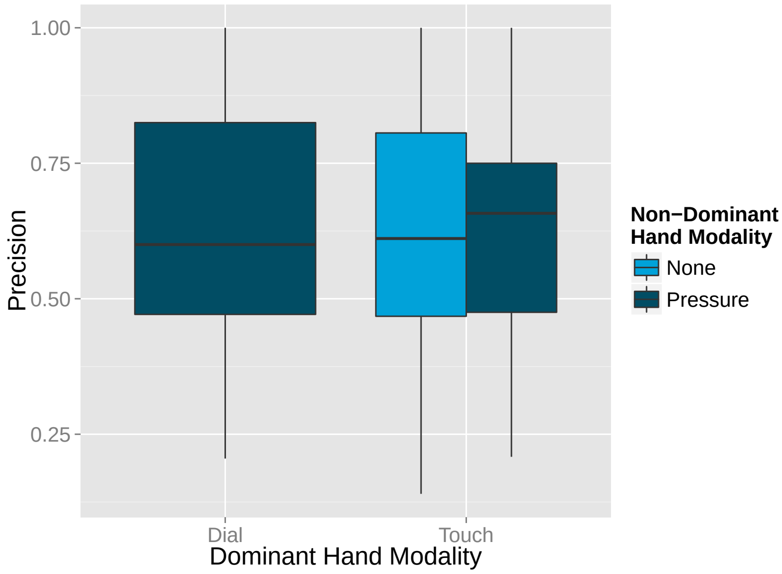


Figure 4.8: Precision from Experiment 4.

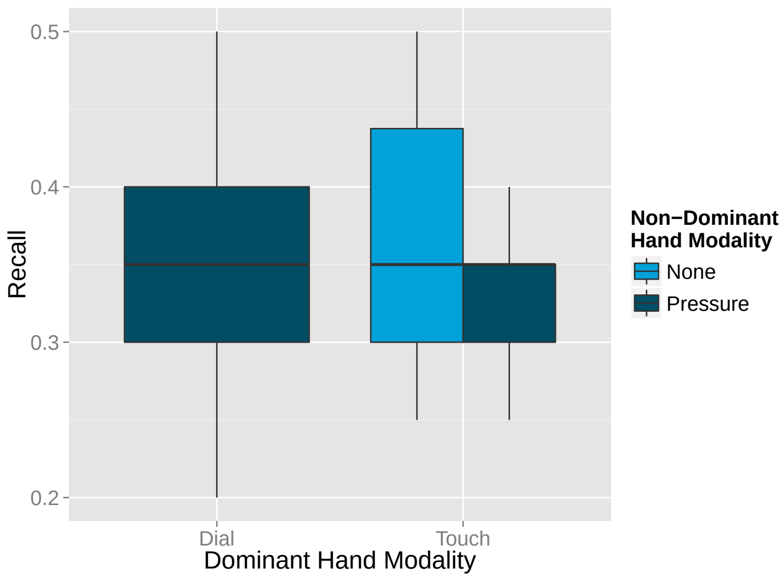


Figure 4.9: Recall from Experiment 4.

4.4.3 Subjective Workload

A repeated measures non-parametric Friedman test of differences was conducted on overall workload scores for each condition in terms of Interaction Technique and was significant ($\chi^2 = 8.9091, p < 0.05$, see Figure 4.10). *Post hoc* Non-parametric Wilcoxon T tests with Bonferroni correction (corrected $p = 0.01$) revealed the Touch technique to have significantly lower subjective workload than the Dial and Pressure ($p < 0.01$) and the Dial and Touch technique ($p < 0.01$).

4.4.4 Discussion

The assumption that 7.5 minutes was a sufficient time limit within which to complete the task turned out to be wrong: no participant in any condition managed to finish the task (find all the relevant images) within the time limit. From observed behaviour during the study, participants tended to over think the task, continually questioning their relevance judgements after having traversed the collection two or three times, often deselecting as many images as they selected in an attempt to keep the number of irrelevant images they selected to a minimum – an instruction given to them before the experiment began. Though not one that had an effect on the task ending before the time limit, since the task would end simply when all relevant images were selected, regardless of the number of irrelevant images. This instruction was given to discourage participants from employing a simple "select all the images" strategy to complete the task. Typically, success in a task like this involves high precision and high recall, which translates into "a high number of relevant images selected and a low number of irrelevant images selected". However, in this context if a technique had higher precision and lower recall than the others it would still have been considered a good result – as long as it was combined with a low task competition time as it would imply that the technique that afforded it allowed participants to see and judge a higher proportion of relevant images. It is possible that providing explicit feedback about the number of relevant images left to select would have mitigated this problem. However, despite the lack of insight from the precision and recall data (see Figures 4.8 and 4.8), in terms of subjective workload the Unimanual Touch technique clearly outperformed both bimanual techniques (see Figure 4.10).

4.5 General Discussion

4.5.1 Unimanual vs Bimanual Scrolling

In general, there was no evidence to suggest that the bimanual scrolling techniques provided any concrete benefit over the Unimanual Touch scrolling technique. In the previous chapter, the bimanual techniques showed a clear advantage over the unimanual techniques in terms of performance and preference, though this result was not replicated here. Previously, the *status quo* unimanual touch scrolling technique had a higher subjective workload score than all the other techniques, whereas here it had the lowest. In both studies, the unimanual touch scrolling technique acted as a baseline and was implemented using the default intertial scrolling exposed through the native SDK from each operating system. In the previous chapter the Windows 7 Surface 2.0 SDK, running on a 10" Viewsonic Viewpad was used, and in this chapter the Android 4.1.1 SDK running on an Asus Transformer Prime. Consider-

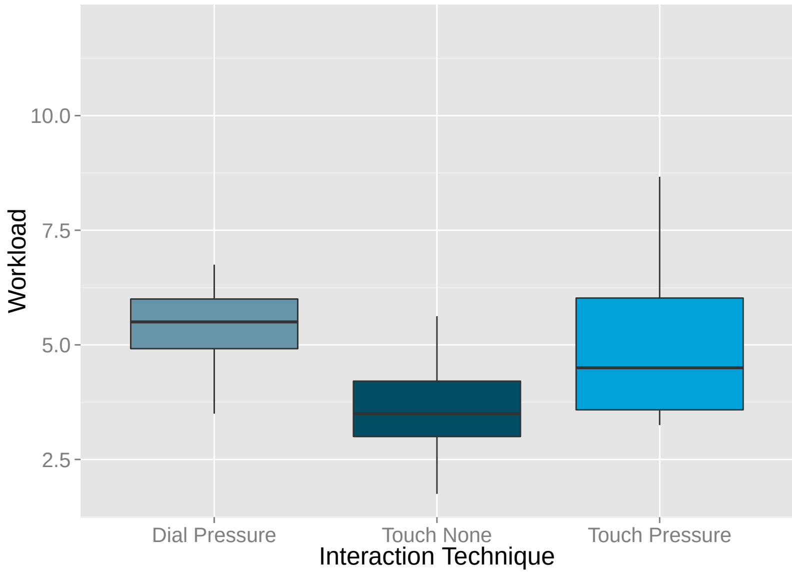


Figure 4.10: Subjective Workload (TLX) from Experiment 4. The Touch technique to have significantly lower subjective workload than the Dial and Pressure $(p < 0.01)$ **and the Dial and Touch technique** $(p < 0.01)$**.**

ing that the latter is a more modern implementation, running on a more modern touchscreen tablet device, the contrasting performance and subjective preferences results across the two chapters would suggest that the difference may rest in the implementation, rather than with a problem in the technique at a more abstract level. If this is the case, then credence should be given to fact that the more modern and refined intertial scrolling implementation from the Android SDK, which has seen wide adoption and acceptance across both tablets and smartphone devices, outperformed the older Windows 7 Surface SDK.

4.5.2 Non-Dominant Hand Modalities

However, participants were able to operate the novel modalities effectively. Furthermore, the evidence suggests that pressure is a more effective auxiliary modality than the touch slider in the context of bimanual scrolling techniques. Pressure was consistently better across both of the dominant hand modalities, whereas the performance of the touch slider was significantly affected by the dominant hand modality used. From the results of the previous chapter, the touch slider resulted in better objective performance (though participants were more likely to overshoot targets over longer distances), though the pressure sensor had a lower subjective workload. Combined with the results of this chapter, it is promising as it suggests that participants can more easily control a pressure sensor when holding a tablet device than a touch slider. However, it is not yet clear what function pressure should have in this context, if any.

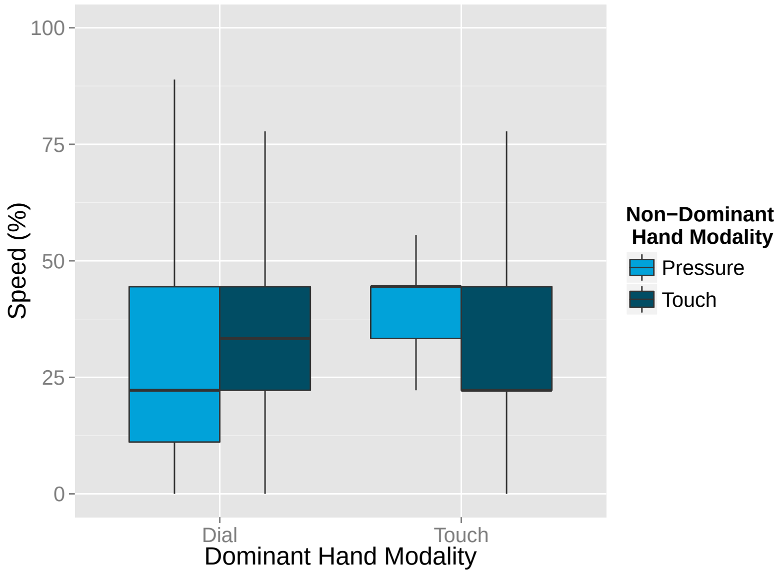


Figure 4.11: Utilisation of Speed from Experiment 3.

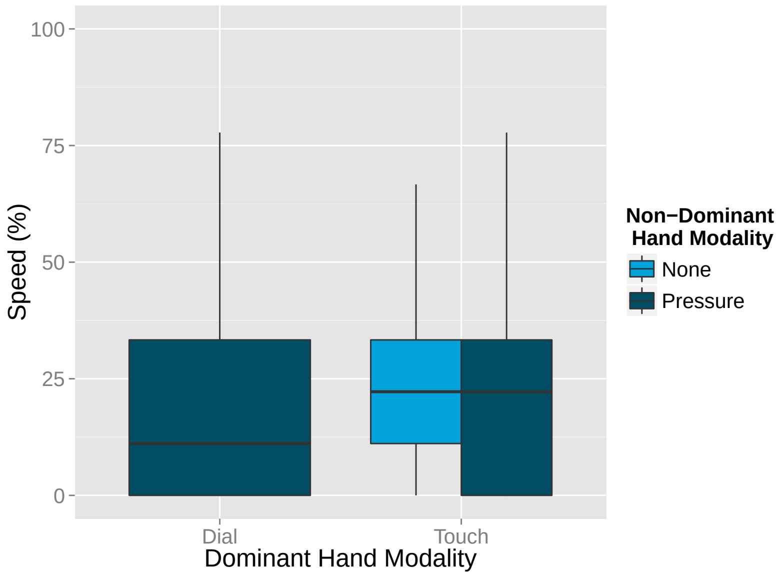


Figure 4.12: Utilisation of Speed from Experiment 4.

4.5.3 Variations in Speed

Figures 4.11 and Figure 4.12 shows the distribution of speed values used across the different modalities in the two studies presented in this chapter. In the previous chapter, it was observed that the distribution of speed values was skewed toward to lower end of the scale for the techniques that used pressure for speed control and is distributed across the centre for techniques that used the on screen slider. From this, it was noted that participants attained higher speeds when using the touch slider, thus accounting for gains in performance. However, the speed values from this experiment do not as easily fit with that analysis. In fact, it can be seen that the use of pressure resulted in a greater variation of speed values, though the values for pressure are still skewed to the lower end of the pressure space. In the literature review, it was noted that pressure input has the unique combination of a natural inverse – like with dials or knobs, there is an obvious and natural way to reverse the action – and the property of *"bounce-back"* – a property that makes a device or modality return to its original state or position soon after the user has relinquished control. The touch slider also had a natural inverse, but did not have the property of *bounce-back*: it did not behave like a spring-loaded slider bar. Considering the distribution of speed values in terms of these properties, we could speculate that the reason the distribution of pressure values is skewed towards the lower end of the pressure space is that the combination of a natural inverse and bounce-back would pull the pressure values down to zero whenever a participant disengaged in someway - whether that be by accidentally slipping off the sensor, or intentionally stopping to evaluate some of the images.

4.6 Task Considerations

With the browsing task, there was no evidence to suggest that the bimanual scrolling techniques offered any concrete benefits over the unimanual equivalents. However, in the previous chapter there was evidence to suggest that the bimanual techniques did offer benefits over the unimanual equivalents. There were differences in the nature of the task that should be considered when interpreting these results. In the previous chapter, the task involved scrolling to and selecting a target from an alphabetically ordered list of artists names. Participants were aware of the fact that the list was ordered in such a way and thus were able to use that to help navigate to the target. In the studies presented in this chapter, no such ordering of the items was available to help participants. Instead, images were presented in a random order and participants had to visually search through the images in order to identify which were relevant and which were not. In both studies, the same number of items were used (320), except in the first the items were alphabetically ordered and in the second they were randomly ordered. From this alone we would expect performance (in terms of task completion time) to increase between the first and second studies [Cockburn and Gutwin, 2009]. However, the browsing study was not a simple "single target selection" task - rather it involved searching for multiple relevant images within the collection, a task that could not be simplified by skipping over items that are known to be irrelevant based on their position in the collection (as would be possible with an ordered collection), further increasing the amount of time we would expect the task to take, as requiring users to make a selection from many choices incurs greater cognitive load and selection time (Hick-Hyman's law [Hick, 1952]).

This in itself is not problematic - the task that was being modeled using the image browsing task (that of visually browsing through a collection of media items) is one that could reasonably be expected to involve a more complex procedure of item evaluation that a visual search task involving the selection of a known item using visual cues. Users often browse through media collections without a particular target in mind [Cunningham *et al.*, 2004] and thus, a task which involves scrolling to and selecting one known target - whether that target is in an ordered or unordered list and whether that target is visually or textually represented - is, I would argue, not sufficiently representative of the real task. For this reason movement time - the base metric used in the standard models of target selection (both Fitts' Law and Hicks Law are based on movement time observations) - was not the primary dependent variable in the browsing study. Instead, precision and recall were used to evaluate the techniques in an attempt to quantify the how effective the techniques were at allowing users not just an effective way to scroll through a collection but also an effective way to see and evaluate the images, since those metrics should allow the quantification of how many images within the set were evaluated. However, with the data gathered using these metrics it was not possible clearly to tease apart the relative metrits and draw backs of the bimanual techniques compared to the unimanual touch technique. Certainly, some of the techniques clearly performed worse than others: the Unimanual Dial was universally bad and there was evidence to suggest that bimanual techniques involving a flat capacitive dial are not as effective as though which use touch input for control of scrolling. It was clear, however, that in terms of subjective workload the unimanual touch technique was superior to the bimanual techniques. This is puzzling because the opposite result was observed in the previous chapter (where the unimanual touch technique had higher subjective workload than the bimanual techniques involving pressure). If we take into account the hardware considerations outlined above (where the poor performance of the unimanual touch technique was attributed to an older Windows 7 touch SDK), one interpretation is that in addition to the extra cognitive load from the task (that we can infer from Hick-Hyman's law) there was also an additional cognitive load on the bimanual techniques over the unimanual touch technique which was amplified by the task difference. If this is the case, we can surmise that the bimanual techniques offer benefits over unimanual equivalents in tasks involving scrolling to and selecting known targets, though these advantages do not translate to more open ended browsing task.

4.7 Conclusions

Research Question 1 asked:

> *Can bimanual input techniques improve scrolling performance on tablet de-*

> *vices?*

From this chapter, there was no evidence to suggest that the bimanual techniques evaluated provided any concrete benefits over unimanual techniques. The bimanual techniques outperformed the Unimanual dial technique, however, there was no evidence to suggest that any of the bimanual techniques provided benefit over Unimanual touch. The Unimanual Touch technique is the *status quo* scrolling technique on commercially available touchscreen tablets and smartphones and so the lack of clear benefit over that technique is more important than benefit over the, more novel (in terms of tablet devices) unimanual dial technique.

Research Question 2 asked:

> *Can novel input modalities (such as pressure) improve performance for bimanual tablet based scrolling interactions?*

The previous chapter concluded that splitting the control of scrolling speed and scrolling direction across two hands is a viable way to scroll on a tablet, which could support simultaneous two-handed input while the user is holding the device. While this is still true – the results from both chapters suggest that users can control scrolling in this way – as discussed above, it shows little benefit over current techniques. The previous chapter concluded that it was unclear whether pressure is a viable modality for providing effective auxiliary input for bimanual interaction techniques on touchscreen tablet devices; however, the results from this chapter do suggest that pressure is a more effective auxiliary modality than the touch slider in the context of bimanual scrolling techniques. S ince it is unlikely that interaction design for touchscreen tablet devices will be best served by using pressure for the control of scrolling speed, the remainder of this thesis will investigate the properties of pressure input that make it suitable as an auxiliary input modality (one that supplements, rather than replaces touch interaction) in the context of bimanual interactions on tablet devices by investigating its impact on existing dominant-hand input techniques.

Chapter 5

Transient Pressure

5.1 Introduction

Whenever pressure is applied, a release of pressure follows. Pressure input has a natural ebb and flow that may be useful in design, but is masked when selection events are imposed. We can model pressure input in a way that includes this flow by considering it in terms of two properties: natural inverse and bounce-back [Ghazali and Dix, 2005]. A modality with a natural inverse has an intrinsic inverse action that produces an opposite effect. An example of which is a dial, which you turn both clockwise and anticlockwise in equal and opposite ways. A modality with bounce-back returns to its initial state soon after the user has relinquished control, e.g. a jog dial. Pressure input has both these properties: when a modality with natural inverse also has the property of bounce back, the natural inverse occurs automatically whenever control is released. We can call this combination *transience*, since the state of the modality only persists during interaction. By modelling pressure in this way, we gain the opportunity for operationalising the continuous application and release of pressure.

Any spring-loaded device with a natural inverse also exhibits the property of transience. A spring-loaded dial or knob (such as on a microwave oven or an egg timer) behaves in a similar way, as does a joystick. The natural inverse that pressure has is worth considering as it embodies a fundamental principle of user interface design and direct manipulation: permit easy reversal of actions [Shneiderman and Plaisant, 2005]. Doing so encourages the exploration of unfamiliar options and assures the user that errors can be undone. Since pressure also has the property of bounce-back, the natural inverse is automatically invoked when the sensor is disengaged, therefore in order to explore the effectiveness of both the applying and releasing pressure in HCI, the selection event has to be decoupled from the control of pressure in an effective way. Here, this is achieved with a bimanual strategy where the selection event is controlled by the dominant hand on the touchscreen.

Previous work in the field has employed a pressure-based linear targeting (PBLT) paradigm in order to measure the precision of applied pressure under various conditions [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004]. As discussed in Chapter 2, this paradigm has been successfully applied to the study of dominant-hand pressure input in the context of unimanual interaction techniques, using pressure based selection techniques such as *Dwell* or *Quick Release*. Performance using these two techniques in the studies described was high and neither are untenable for effective one-handed pressure input. However, by removing the need for a selection event, we can model pressure as a *transient* modality – a potentially useful characterisation that may make it more effective for interaction design.

In this chapter, the precision of applied pressure is studied using a PBLT task where the selection event is triggered by the dominant hand on the touchscreen with the goal of studying pressure as a functional primitive, without implying any particular application. In doing so, use of pressure as an auxiliary input modality (one that supplements, rather than replaces touch interaction) can be investigated by evaluating its impact on existing dominant-hand input techniques and *vice versa*, while also preserving the transient properties of pressure input. Therefore, Research Question 3 asks:

> *RQ3: How accurately can users perform a two-handed combination of pressure and touch input while holding the device?*

It is also of interest to study the effect of **Maintaining** a constant level of pressure *over time*. How accurately users can maintain a particular level of pressure is an understudied area in the literature, the closest being the study of dwell times for the Dwell selection technique (typically $\sim$1s) [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004]. Here, much longer times are considered. By exploring how accurately users can maintain pressure over time, the design space of pressure based interactions that would allow pressure to affect the interface for a sustained period of time can be explored, e.g. for mode switching, kinaesthetic feedback has been shown to reduced mode errors and reduce cognitive load [Sellen *et al.*, 1992]. Therefore, Research Question 4 asks:

> *RQ4: How accurately can users maintain different levels of pressure during a bimanual interaction?*

Two experiments were carried out to study the effects of pressure input on touchscreen input and *vice versa*. In the first, simple touchscreen *taps* are evaluated and in the second more complicated touchscreen *gestures* are considered.

5.2 Experiment 5: Dominant Hand Tapping

An experiment was carried out to explore the usability of pressure as an auxiliary input modality. The aim was to explore the combination of transient pressure and touch input on tablet devices. Dominant hand *taps* were selected to begin with for their simplicity.

For this study, Research Question 3 was split into two blocks: **Targeting** and **Moving**.

Targeting If pressure is to be used to supplement conventional touch input on a tablet device, it is desirable to know how accurately people can apply pressure with their NDH while simultaneously interacting using their DH. This block was designed to assess how accurately participants could apply pressure as part of a bimanual interaction. Within each condition, a trial consisted of a single selection - one pressure menu selection followed by one touchscreen selection. Thus, the evaluation of pressure control is similar to the PBLT tasks in [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004], where accuracy is assessed from zero (no pressure applied) to the target pressure. Though where previous work has assessed DH pressure accuracy, here NDH pressure accuracy is assessed. There have been few studies investigating NDH pressure input. Some applications of NDH pressure have been considered (such as [Holman *et al.*, 2013]) though, the precision of applied pressure was not evaluated. In addition, instead of providing a pressure selection mechanism (such as Quick Release or Dwell), here selections were achieved using the DH on the touchscreen.

Moving This block was designed to assess how accurately participants could navigate between pressure targets by both applying and releasing pressure. Bidirectional movement, and movement from one non-zero pressure target to another, is understudied in the HCI literature, with most pressure studies only assessing accuracy from zero to the target (as in [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004]). However, knowledge of how accurately users can navigate from one non-zero pressure target to another is of value as it would enable designers to exploit the natural inverse of pressure input.

There was also a block for Research Question 4, which assessed the effect of **Maintaining** pressure over time. Therefore, the experiment was split into three blocks, **Targeting, Moving** and **Maintaining**. Specific details for each block are given in a dedicated section below.

Experimental Design

The research questions were evaluated in a single study that consisted of three blocks, each investigating one of the questions outlined above (Targeting, Moving, Maintaining), in a single session. Across all blocks, participants controlled pressure using a ‘pinch-grip’ with their NDH via a force-sensing resistor (FSR) mounted on the bezel of a tablet device while performing a targeting task on the touchscreen of the device with their DH. Participants supported the tablet with their NDH while resting it on their lap with the device tilted towards their face (see Figure 5.2). Each block required a different method of pressure control, and had a different set of dependent and independent variables, all of which are described in detail in a dedicated section below. All pressure values are reported in Newtons (N).

All participants took part in all three blocks within one session that lasted about an hour. The order of the blocks was counterbalanced using a latin square.

Apparatus

The force applied by the user was measured using an Interlink Electronics Force Sensitive Resistor (FSR) [1]. The conductance of this sensor is linearly proportional to force within human ranges. As current flow is linear with conductance, we use a transimpedance amplifier or 'current-to-voltage convertor' to obtain a voltage that represents force. This approach takes advantage of an inherently linear property of the sensor, avoiding the issues of non-linearity seen in prior work [Stewart *et al.*, 2010, Wilson *et al.*, 2010]. This setup resulted in a pressure space of 10N, that was used across all experimental blocks. An mbed micro-controller [2] was used to connect the FSR to a Microsoft Surface Pro tablet running Windows 8, which ran the experimental software. A low-pass filter was used to reduce noise from the raw sensor values.

Participants

Eighteen right-handed participants, (6 Female, 12 Male) aged between 19-37 years old (M=22.5) took part from the study, 6 of whom were tablet users, none of whom suffered from colour blindness. Participants were paid £6 for participation.

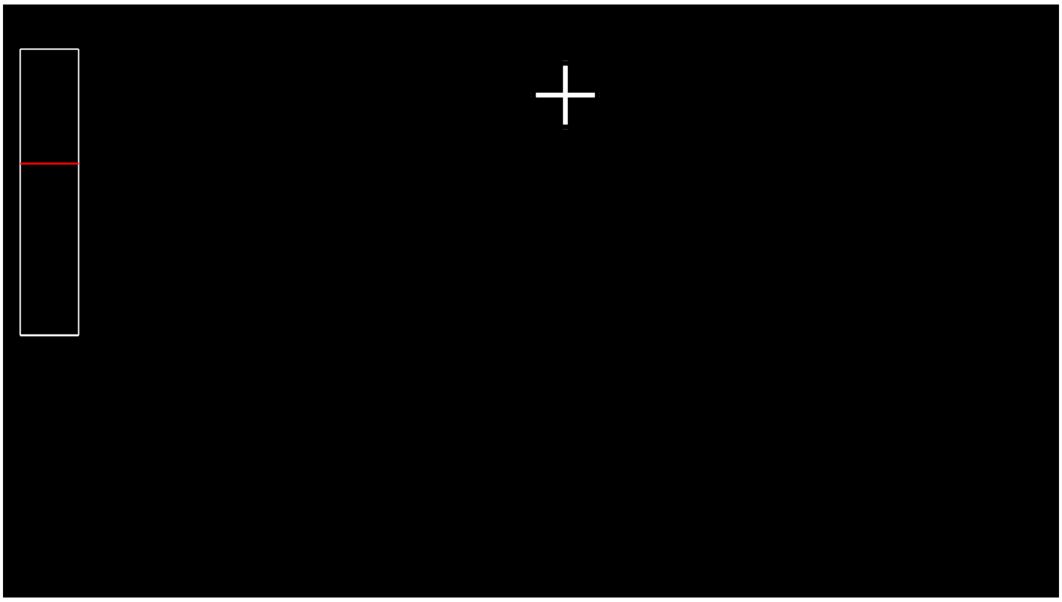
5.2.1 Targeting

In the Targeting block, the experimental task involved selecting sequences of pressure and touch targets. Pressure targets were selected by applying force to the FSR mounted on the bezel of the device, which moved a cursor up and down a linear menu of coloured targets (see Figure 5.1a) (applying pressure moved the cursor up, releasing it moved the cursor back down). Touch targets were selected by tapping with a single finger on a crosshair

[1] Described in `http://www.digikey.co.uk/Web\%20Export/Supplier\%20Content/InterlinkElectronics_1027/PDF/Interlink_Electronics_Integration_Guide.pdf?redir`

[2] `www.mbed.org`

(a) Targeting/Moving Conditions. 7 item menu shown.



(b) Maintaining Condition. 6N target shown.

Figure 5.1: Experimental Interfaces from Experiment 5. In each screenshot, the pressure menu is on the left hand side and a touch target is on the right.

Figure 5.2: Participant during the Experiment 5. Pressure input is controlled via an FSR under the thumb of his non-dominant hand (left-hand), while he holds the tablet as it rests on his lap. Targets are selected on the screen using his dominant hand.

displayed on the touchscreen (see Figure 5.1b). Across all conditions, touch targets were displayed randomly from a grid of targets across the screen. For each selection, a single crosshair would appear, the colour of which would signify the item to be selected in the pressure menu. Participants were instructed to first navigate to the corresponding colour in the pressure menu and maintain that level of force while they selected the crosshair. This counted as a single selection. A border around the main screen and a circular border around the DH crosshair target also provided visual feedback for pressure input - both would change colour to correspond to the pressure cursor's current position in the menu. This meant that participants would not have to rely solely on the visual feedback provided from the menu itself. Participants were instructed to lift their hand from the pressure sensor after each selection to ensure they started each trial at zero.

Variables and Measures

The independent variables were *Menu Size* - the number of targets in the pressure menu (0 Item, 5 Items, 7 Items, 10 Items). The 0 item (control) condition acted as a baseline for DH performance. In it, participants only had to select targets with their DH, while holding the device and no pressure had to be applied. For the other menu sizes, the pressure space was divided evenly between menu items to create target widths of 2N for the 5 item menu, 1.4N for the 7 item menu and 1N for the 10 item menu.

Since there were an uneven number of targets in the different menu sizes, 4 common *Target Distances* (2N, 4N, 6N, 8N) were used to compare across menu sizes. This meant that not all the items in each menu were selected, though it meant the same number of selections were made in each condition. This approach has been used successfully in previous pressure input studies [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004].

The dependent variables were: *Selection Time* - the time it took to perform a complete selection (navigate to a pressure target and then select a touch target); *Pressure Target Accuracy* - whether the correct item was selected in the pressure menu (the (0 item) control condition was not considered in the Pressure Target Accuracy analysis) and *Dominant Hand Error Distance* - how accurate the DH target selection was (measured as the Euclidean distance of the touch point from the centre of the touch target). *Target Distance* - the 4 common target distances mentioned above (2N, 4N, 6N, 8N) - was considered as a dependent variable in the Pressure Target Accuracy analysis, but not in the Selection Time or DH Error Distance analyses, as Target Distance was not applicable to (0 item) control condition.

There were four conditions, one for each Menu Size, counter balanced using a latin square. The order of the trials within each condition was randomised. In total there were 18 participants x 4 Menu Sizes x 4 Common Target Distances x 2 Repetitions = 576 trials in the Targeting block.

Hypothesis

H 1: Pressure targeting will be faster and more accurate in the conditions with fewer Menu Items, measured by lower Selection Times and higher Pressure Target Accuracy.

H 2: Pressure Targeting will be faster and more accurate in the conditions with shorter Target Distances, measured by lower Selection Times and higher Pressure Target Accuracy.

H 3: Dominant-hand targeting will be more accurate in the conditions with fewer Menu Items, measured by lower Dominant-hand Error Distance.

Results

Selection Time

A one-way repeated measures ANOVA on *Selection Time* showed a significant main effect for Menu Size $F(3, 51) = 151.928, p < 0.001$. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.008$) revealed that participants selected targets significantly

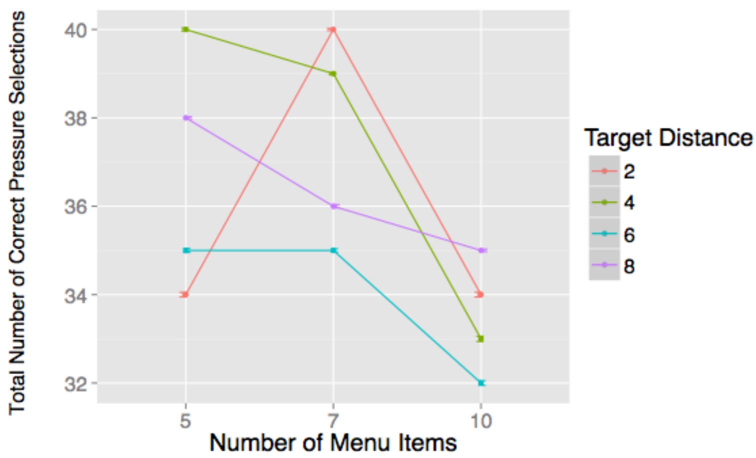


Figure 5.3: Total correct pressure selection across Menu Size and Distance. Participants were significantly more accurate in the 7 item menu condition than the 10 item menu condition $(p < 0.01)$**.**

faster in the control condition (Menu Size = 0) than all other conditions $(p < 0.008)$ and that participants selected targets significantly faster in the 5 item condition than the 10 item condition $p = 0.008$.

Pressure Target Accuracy

Overall pressure accuracy was high (93.07%) across all menu sizes. An overview of Pressure Target Accuracy can be found in Figure 5.3 A two-way repeated measures ANOVA on pressure accuracy showed a significant main effect for Menu Size $F(2, 34) = 3.746, p < 0.05$, no significant main effect for Target Distance $F(3, 51) = 1.265, p = .296$, and no significant interaction between the two $F(6, 102) = 1.063, p = .390$. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.01$) revealed that participants were more accurate in the 7 item menu condition than the 10 item menu condition $(p < 0.01)$.

Dominant Hand Error Distance

There was no evidence to suggest that Menu Size had any effect on dominant hand target accuracy: a one-way repeated measures ANOVA on dominant hand error distance showed no significant effect $F(3, 51) = .689, p = .563$.

Menu Size	Selection Time (ms)	DH Error Distance (px)	Pressure Accuracy
Control (0 Items)	649.85 *(SD = 123.7)*	21.8 *(SD = 9.8)*	N/A
5 Items (W = 2N)	2334 *(SD = 415.9)*	27.5 *(SD = 32.5)*	93.6%
7 Items (W = 1.4N)	2520.2 *(SD = 393.9)*	18.8 *(SD = 6.5)*	96.1%
10 Items (W = 1N)	2889.5 *(SD = 612.2)*	25.3 *(SD = 24.7)*	89.3%

Table 5.1: Mean Selection Time, Dominant Hand Target Error Distance and Pressure Accuracy values for each Menu Size in the Targeting Condition. W = Width of the targets in Newtons.

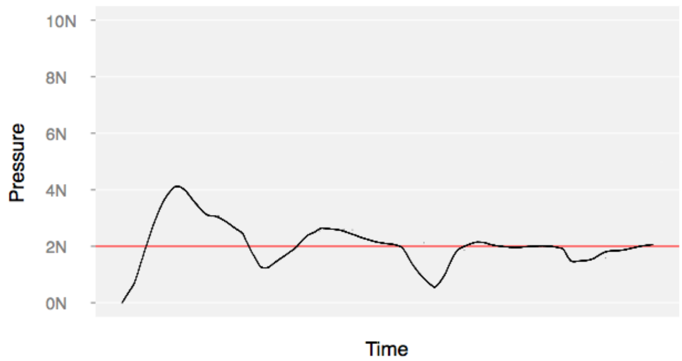
Discussion

Table 5.4 summarises the results from the Targeting block and a histogram of the pressure input in this block is shown in Figure 5.11a. The results were promising. Pressure Target Accuracy was high across all conditions and DH Error Distance was low. Participants were able to select targets significantly faster in the control condition, though this is unsurprising as applying pressure before a selection takes time. There was no evidence to suggest that selecting and holding pressure targets during DH selection had any effect on DH Error, meaning we do not have any evidence to support H3.

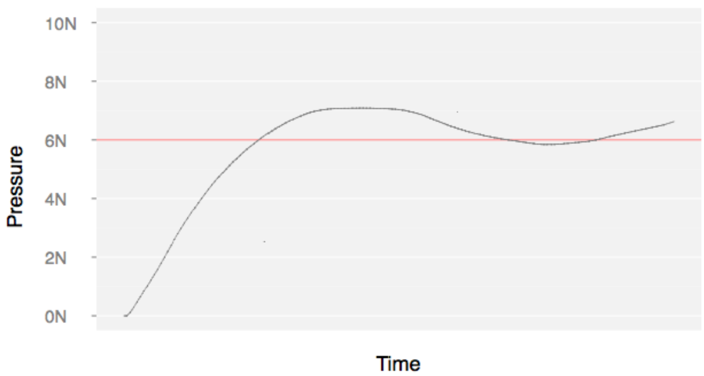
The fact that participants were significantly slower at selecting targets in the 10 menu item condition than 5 item condition was also not surprising, as targets in the 5 item condition were double the size (2N wide, as opposed to 1N in the 10 item conditions) and so were easier to select. Participants were also significantly more accurate when selecting targets in the 7 item condition than in the 10 item condition. Both of these results lend support to H1. There was no evidence that Target Distance had any effect on Pressure Target Accuracy, leading to the rejection of H2.

5.2.2 Moving

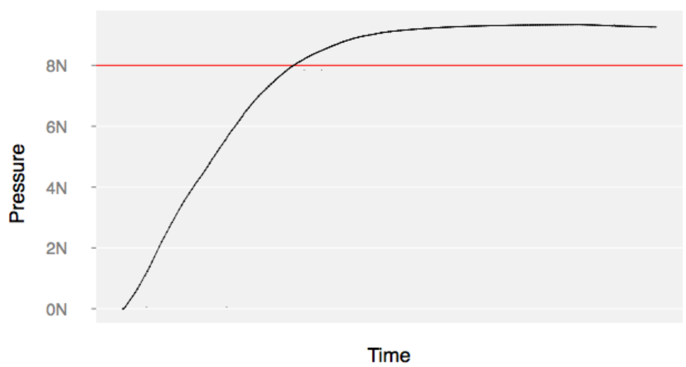
The goal of the Moving block was to assess how well users could navigate between two non-zero pressure targets, by either applying or releasing pressure. In this block, a trial consisted of two selections, using the same experimental task as the Targeting block. Participants were instructed to select a pressure target with their NDH, followed by a DH touchscreen target, followed by another NDH pressure target, followed by a final DH touchscreen target, in succession. To begin, participants would navigate from zero to one of the common starting



(a) 2N Target Menu Distance, Size 10.



(b) 6N Target Menu Distance, Size 10.



(c) 8N Target Distance, Menu Size 10

Figure 5.4: A sample of individual traces from the 10 Item Menu Size trials in the Targeting Block.

positions (2N for up trials or 8N for down trials). From the 2N starting position for up trials, participants would apply pressure (navigate up the menu) to the second target and from the 8N starting position for down trials, participants would release pressure (navigate down the menu) to the second target. There were three common target distances (2N, 4N, 6N) that defined how far the second target would be from the first. Figure 5.5 contains example Up and Down trials from the Moving block.

Variables and Measures

The independent variables were: *Menu Size* - the number of targets in the pressure menu (5 Items, 7 Item, 10 Items); *Direction* - the direction that had to be travelled to get from the starting position to the final target (Up or Down), all Up trials started at 2N and all Down trials started at 8N and *Target Distance* (2N, 4N, 6N) - the distance from the starting point to the target.

The dependent variables were the same as the Targeting block: *Selection Time*, *Pressure Accuracy* and *Dominant Hand Error Distance*. There were three conditions, one for each Menu Size, counterbalanced using a latin square. The order of the trials within each condition was randomised. In total there were 18 participants x 3 Menu Sizes x 2 Directions x 3 Target Distances x 2 Repetitions = 648 Trials.

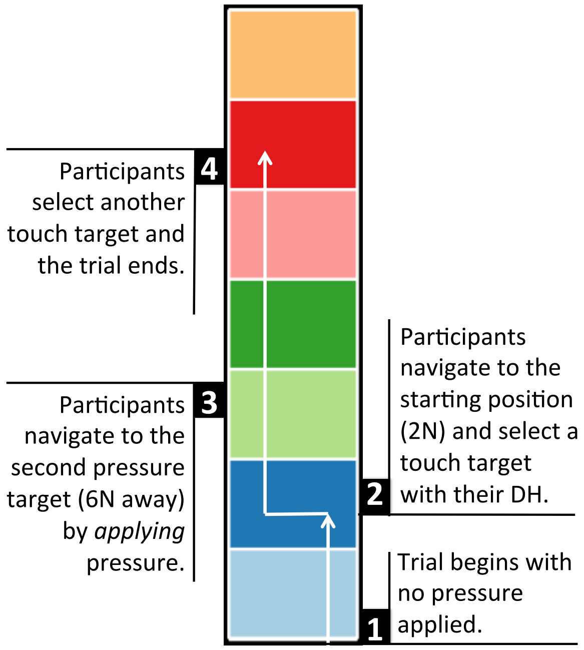
Hypothesis

H 4: Pressure targeting will be faster and more accurate in the conditions with fewer Menu Items, measured by lower Selection Times and higher Pressure Target Accuracy.

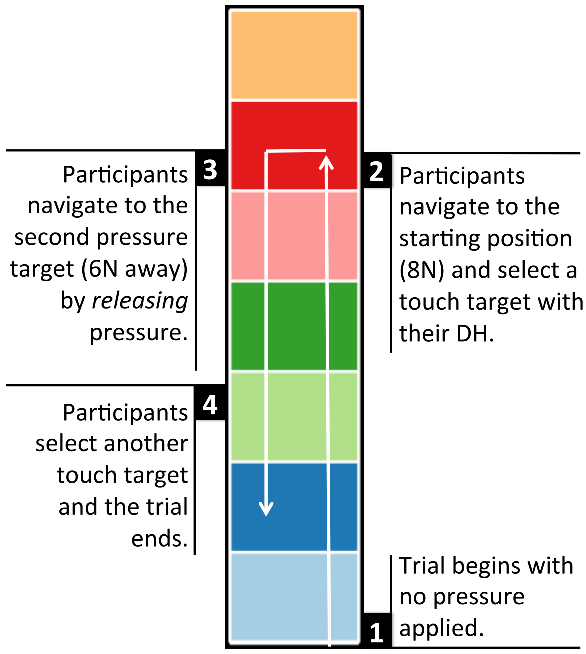
H 5: Pressure targeting will be faster and more accurate in the trials involving Up selections than in those involving Down selections, measured by lower Selection Times and higher Pressure Target Accuracy.

H 6: Dominant-hand targeting will be more accurate in the conditions with fewer Menu Items, measured by lower Dominant-hand Error Distance.

H 7: Dominant-hand targeting will be more accurate in the trials involving Up selections than in those involving Down selections, measured by lower Dominant-hand Error Distance.



(a) An Up trial.



(b) A Down Trial.

Figure 5.5: Example trials from the Moving block in Experiment 5. In each, the participant first navigates to a pressure target starting position, then selects a touch target, navigates to a second pressure target and selects another touch target. In both cases, the target distance is 6N.

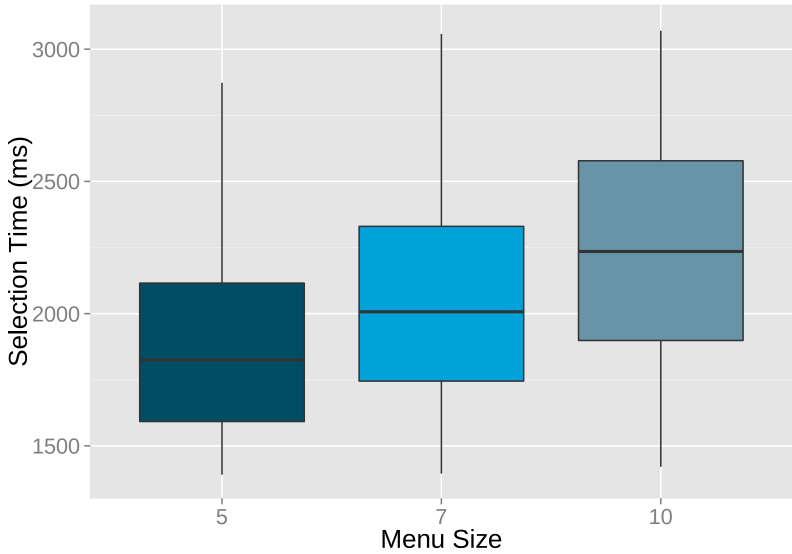


Figure 5.6: Selection Times from the Moving block in Experiment 5. Selection Times for Menu Sizes the Moving Conditions, differences between the Menu Sizes are all significant.

Results

Selection Time

A three-way repeated measure ANOVA on selection time revealed a significant main effect for Menu Size $F(2, 34) = 21.394, p < 0.001$, a significant main effect for Direction $F(1, 17) = 7.688, p < 0.05$ and a significant main effect for Target Distance $F(2, 34) = 27.260, p < 0.001$. There was also a significant effect for the Direction x Distance interaction $F(2, 34) = 7.476, p < 0.05$ as well as the Menu Size x Direction x Distance interaction $F(4, 68) = 3.879, p < 0.05$. No other interactions were significant.

Figure 5.6 gives an overview of the Selection Times. *Post hoc* pairwise comparisons with Bonferroni correction revealed a significant difference in Selection Times between all of the menu sizes ($p < 0.01$), a significant difference between the directions ($p < 0.02$, Down: M=2251.6 ms, Up: M=2065.1ms) and a significant difference between the 2N distance and both the 4N and 6N distances ($p < 0.01$) (see Figure 5.7). In terms of the Direction x Target Distance interaction, there was a significant difference between the Down 6N condition with the Down 2N ($p < 0.003$), Down 4N ($p < 0.003$), Up 2N ($p < 0.003$), Up 4N ($p < 0.003$) and Up 6N ($p < 0.003$) conditions as well as between the Up 2N condition with the Down 4N ($p < 0.003$), Up 4N ($p < 0.003$) and Up 6N ($p < 0.003$) conditions (see Figure 5.7).

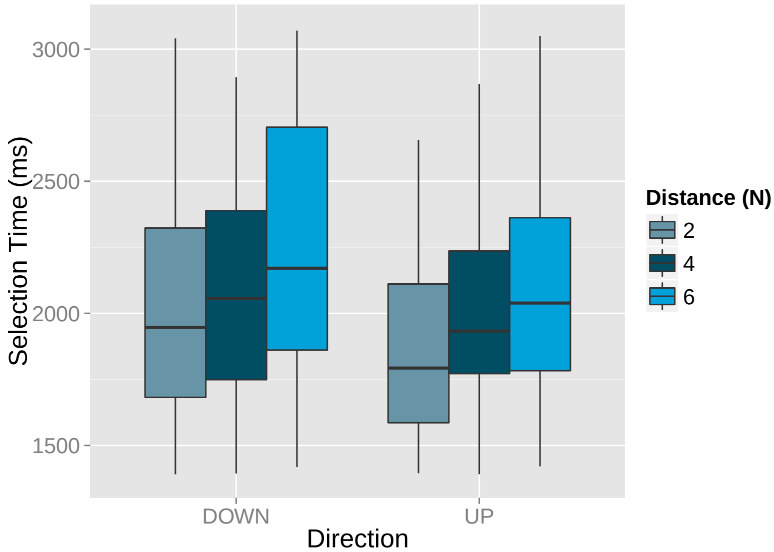


Figure 5.7: Selection Times from the Moving block in Experiment 5. Interaction between Direction and Target Distance in the Moving Conditions in terms of Selection Time.

Pressure Accuracy

There was no evidence to suggest that Menu Size, Distance or Direction had any effect on Pressure Accuracy. A three-way repeated measure ANOVA on *Pressure Accuracy* revealed no significant main effect for Menu Size $F(2,34) = 1.699, p = .199$, or for Direction $F(1,17) = .738, p = .403$, or Distance $F(2,34) = 2.038, p = .147$. There were no significant interactions.

Dominant Hand Error Distance

There was no evidence to suggest that Menu Size, Distance or Direction had any effect on Dominant Hand Error Distance. A three-way repeated measure ANOVA revealed a no significant main effect for Menu Size $F(2,34) = .666, p = .521$, or for Direction $F(1,17) = .010, p = .920$, or Distance $F(2,34) = 1.254, p = .299$. There were no significant interactions.

Discussion

In general, there was no evidence to suggest that either Menu Size, Direction or Distance had an effect on either Pressure Accuracy; however, there was a significant difference between all of the independent variables in terms of selection time, so perhaps participants were trading speed for accuracy. Figure 5.6 gives an overview of the Selection Times and Figure 5.11b shows a histogram of pressure input in this block, pressure input is concentrated in the middle section of the pressure space, reflecting the movement between two non-zero pressure targets in this block. Participants were faster when selecting items in smaller menu sizes, lending some support to H1 (smaller menu sizes had bigger targets) and when selecting targets that were shorter distances away, as would be expected. Participants were also slower when selecting targets that involved the release of pressure (moving down the menu, M=2251.6 ms) than selecting those that involved applying pressure (moving up the menu, M=2065.1ms), lending some support to H2. However there was no evidence to suggest that the Direction had any effect on Pressure Target Accuracy - a promising result in terms of utilisation both the application and release of pressure. Figure 5.7 shows the interaction between Distance and Direction. Here, the fact that the Down 6N combination and the Up 2N combination differed significantly from a number of others can be explained by the fact that it was the slowest and fastest combination, respectively. Clearly, it took people longer to travel further distances, but perhaps releasing pressure accurately over long distances (as opposed to simply letting go of the sensor, which could be carried out quickly) is generally slower than applying pressure over long distances.

In this block, participants always navigated to the final target from another non-zero position (either 2N or 8N), which allowed us to fairly assess the effect of Direction. However, this is unusual in itself since most studies on pressure in HCI evaluate performance from zero. So, although we did not compare them directly, it is interesting to note that the overall accuracy figures by Menu Size from the Targeting block (see Table 5.4) are comparable to those from this block - 5 Items 95.3%, 7 Items 92% and 10 Items 89%. There was no evidence that Menu Size, Distance or Direction had any effect of Dominant-hand Error Distance leading to the rejection of H3 and H4.

5.2.3 Maintaining

In this block, participants were instructed to navigate to a particular level of pressure (by applying force and moving the pressure cursor as before) within the pressure space. However, this time the target pressure was indicated by a single red line within the pressure space (see Figure 5.1b). This was because participants did not need to change the level of pressure applied. Participants had to maintain that level of pressure as accurately as possible while selecting targets, which were displayed randomly from the same grid of targets used in previous conditions, with their DH until the condition ended. Each trial lasted for either 5, 10, 15 or 20 seconds. Participants would continue to select DH targets, while maintaing the target level of pressure, until the trial ended.

Variables and Measures

The Independent Variables were: *Target Pressure* - the amount of pressure that was to be maintained in the particular condition (2N, 4N, 6N, 8N) and *Maintain Time* - the amount of time for which participants were required to maintain the Target Pressure (5s, 10s, 15s, 20s).

The Dependent Variables were: *Pressure Error* - defined as the difference between geometric mean of all the sampled pressure values within a trial and the Target Pressure - this allowed us to asses how close to the Target Pressure participants were during the trial; *Pressure Variance* - the variance of all the sampled pressure values within a trial - this allowed us to assess by how much participants deviated from the Target Pressure during the trial; *Target Selection Time* - the time it took participant to select each dominant hand target within a trial - and *Dominant Hand Error Distance* - how accurate the DH target selection was (measured as the Euclidean distance of the touch point from the centre of the touch target) - both of which allowed us to measure if the different levels of pressure affected DH performance.

There were four conditions, one for each Target Pressure, counterbalanced using a latin square. The order of the Maintain Times was randomised within each condition. In total there were 18 participants x 4 Target Pressures x 4 Maintain Times x 2 Repetitions = 576 Trials.

Hypothesis

H 8: Pressure Accuracy will decrease as Maintain Time increases, measured as high Pressure Error and High Pressure Variance.

H 9: Pressure Accuracy will decrease as Target Distance increases, measured as high Pressure Error and High Pressure Variance.

H 10: Dominant-hand targeting will be more accurate in the trials with shorter Maintain Times, measured by lower Dominant-hand Error Distance and faster Target Selection Time.

Results

Pressure Error

An overview of the Pressure Error results can be found in Figure 5.8. A two-way repeated measures ANOVA on *Pressure Error* showed a significant main effect for Target Pressure, $F(3,48) = 2.879, p < 0.05$, no main effect for Maintain Time, $F(3,48) = 1.231, p = .309$ and no interaction between the two, $F(9,144) = .666, p = .739$. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.008$) revealed that the pressure error for the 8N targets was significantly lower than the 2N targets ($p < 0.008$) (see Figure 5.8).

Pressure Variance

A two-way repeated measures ANOVA on *Pressure Variance* showed a significant main effect for Target Pressure, $F(3, 48) = 9.241, p < 0.001$, no main effect for Maintain Time, $F(3, 48) = 2.656, p = .059$ and no interaction between the two, $F(9, 144) = .891, p = .535$. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.008$) revealed that the pressure variance for the 8N targets was significantly lower than the 2N targets ($p < 0.008$) and the 4N targets ($p < 0.008$) (see Figure 5.9).

Target Selection Time

There was no evidence to suggest that Target Pressure or Maintain Time had any effect on Target Selection Time. A two-way repeated measures ANOVA on *Target Selection Time* showed no significant main effect for Target Pressure, $F(3, 51) = .523, p = 0.668$, no significant main effect for Maintain Time, $F(3, 51) = .297, p = 0.827$ and no signifiant interaction between the two $F(9, 153) = .663, p = 0.768$.

Dominant-hand Error Distance

There was no evidence to suggest that Target Pressure or Maintain Time had any effect on Dominant-hand Error Distance. A two-way repeated measures ANOVA on *Dominant-hand Error Distance* showed no significant main effect for Target Pressure, $F(3, 51) = .355, p = 0.786$, no significant main effect for Maintain Time, $F(3, 51) = 1.222, p = 0.311$ and no signifiant interaction between the two $F(9, 153) = 1.209, p = 0.294$.

Discussion

In general, Pressure Variance and Pressure Error decreased as Target Pressure increased (see Table 5.2) with values for the 8N condition being significantly lower than the 2N condition in terms of Pressure Error (see Figure 5.8) and significantly lower than both the 2N and 4N conditions in terms of Pressure Variance (see Figure 5.9), leading to a rejection of H2. Since the pressure space was 10N wide, participants could still overshoot the 8N Target Pressure (the effective width of the last menu item was not infinite) and so the results here strongly suggest that maintaining pressure is more accurate as Target Pressure increases. This can

Target Pressure	Mean Pressure Variance (N)	Mean Pressure Error (N)
2N	0.633	0.152
	(SD = 0.51)	*(SD = 0.12)*
4N	0.362	0.162
	(SD = 0.23)	*(SD = 0.16)*
6N	0.271	0.135
	(SD = 0.35)	*(SD = 0.09)*
8N	0.11	0.096
	(SD = 0.09)	*(SD = 0.09)*

Table 5.2: Mean Pressure Variance and Pressure Error values for each Target Pressure in the Maintain Condition from Experiment 5.

be seen in Figure 5.11c, where pressure input is concentrated more narrowly around the 8N target than the 2N target and pressure input above 8N (towards the end of the pressure space) tapers off sharply. There was no evidence from the Targeting or Moving blocks that would suggest selecting targets in the lower levels of the pressure space was less accurate, though since there was no evidence in this condition to suggest that Maintain Time had any effect on performance (leading to a rejection of H1), the results cannot be attributed to fact that participants were applying pressure for longer. In addition, previous work has found accurate performance using a much smaller (3.5N) pressure space [Wilson *et al.*, 2011, Wilson *et al.*, 2010], further suggesting that accuracy in the lower regions of the pressure space is not in itself problematic.

Due to the fact participants had to maintain a grip on the tablet device during the task, applying lower levels of pressure may have been more difficult because it involved applying less pressure than they normally would have while gripping the tablet, leading to instability. This problem may have been mitigated in previous conditions due to participants only having to apply pressure in short bursts. However, since gripping pressure was not measured, this is only speculation. Comparing the Pressure Error and Variance values to the Menu Sizes used in the Targeting and Moving Conditions - where targets were 1N, 1.4N or 2N wide - would suggest that users could maintain pressure adequately within those targets across the pressure space. If it is the case that applying smaller amounts of pressure over time is more difficult when gripping the device because it requires less force than a normal grip, it may be possible to mitigate this problem by measuring a baseline ‘grip-pressure’ - the normal amount of pressure applied while holding the device - that could be used as a zero-value.

There was no evidence that Target Distance or Maintain Time had any effect of Dominant-hand targeting accuracy, leading to a rejection of H3.

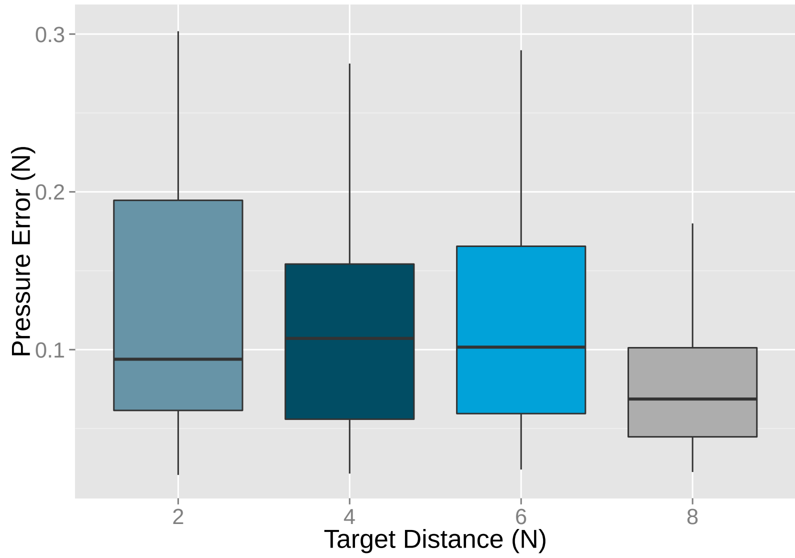


Figure 5.8: Overview of the Pressure Error values for each Target Pressure in the Maintain Condition from Experiment 5. Pressure Error for the 8N targets was significantly lower than the 2N targets $(p < 0.008)$**.**

5.2.4 Discussion

The use of pressure as a NDH input modality to supplement DH touch interaction was successful. There was no evidence to suggest that pressure input, in any of the configurations tested, had any effect on DH accuracy. Furthermore, Pressure Accuracy was high across all three studies. Participants were able to accurately select pressure targets, by both *applying* and *releasing* pressure as well as accurately maintaining pressure over time.

Participants could accurately select targets by *releasing* pressure as well as by *applying* pressure from a non-zero starting point. The mean pressure accuracy for the Down selections in the Moving block was 89%, while the mean pressure accuracy for the Up selections was 94.9%; however, Down selections were significantly slower than Up selections. This provides support for the goal of operationalising both the release and application of pressure, which allows designers to exploit the natural inverse of pressure input.

Finally, the results show that the people can maintain pressure more accurately as the target pressure increases, which suggests it could be valuable to explore interfaces that increase the amount of key content available as the amount of pressure applied increases. This could be translated into what Pohl and Murray-Smith [Pohl and Murray-smith, 2013] call the 'focused-casual' continuum, where users can vary their level of engagement to suit their physical, social or mental context. Increasing pressure could increase engagement with a system, making more content or functionality available in the process. When less interested in engaging with their device users could apply little or no pressure, allowing the system to make decisions for them.

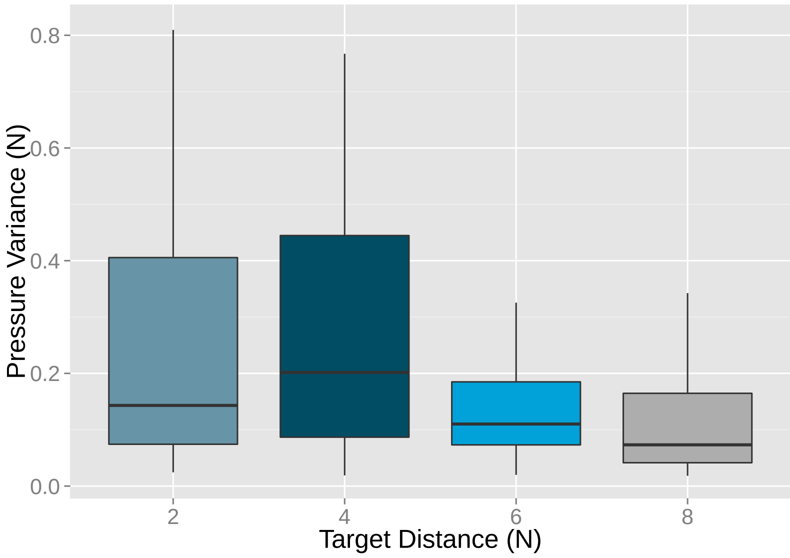
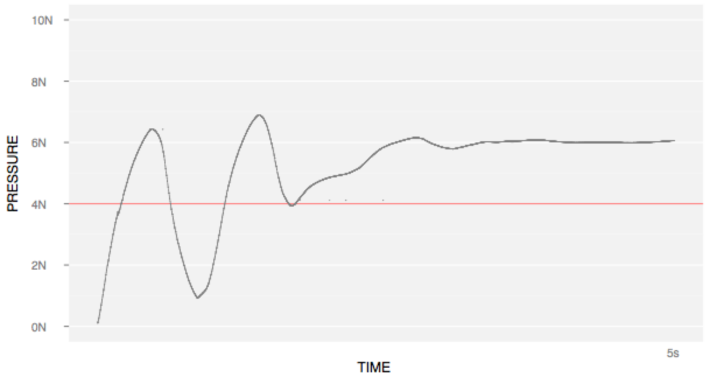


Figure 5.9: Overview of the Pressure Variance values for each Target Pressure in the Maintain Condition from Experiment 5. Pressure Variance for the 8N targets was significantly lower than the 2N targets $(p < 0.008)$ **and the 4N targets** $(p < 0.008)$ **.**

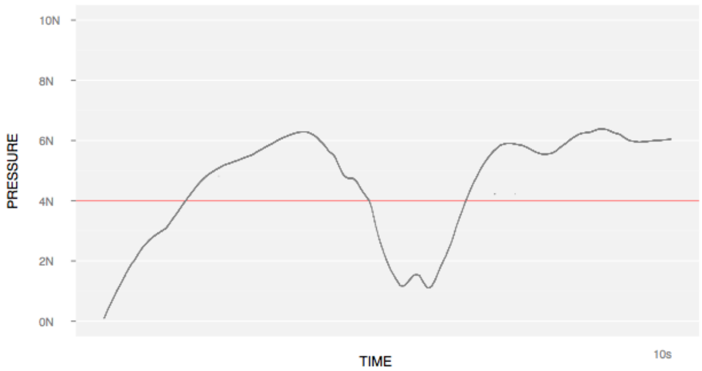
In conclusion, the results from this study suggest that characterising pressure as a *transient* modality - one that has a natural inverse, bounce-back and a state that only persists during interaction - results in high levels of accuracy for NDH pressure input, with low impact on dominant hand targeting. While the results are promising, the dominant-hand action used is not fully representative of the full range of available touchscreen input, in which single and multitouch gestures are common. In the following section, the effect of such complex gestures will be considered.

5.3 Experiment 6: Dominant Hand Gestures

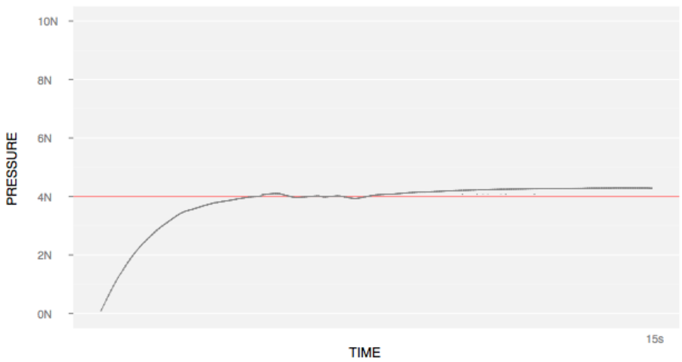
In the previous section, pressure was investigated as an auxiliary input modality (one that supplements, rather than replaces touch interaction) in three studies that assessed how well people could hold the device and control pressure input with their non-dominant hand (NDH) while simultaneously interacting using their dominant hand (DH). However, the study only evaluated the use of NDH pressure and DH *tap* gestures. In typical touchscreen tablet interfaces, the DH carries a greater function than simply making tap-based selections. Gestures such as pinch, swipe and rotate produce a rich repertoire of DH action, creating a powerful input vocabulary that forms the basis of modern touchscreen interaction. Given that these DH gestures are more complex than taps, it is not clear what effect simultaneous pressure input from the NDH might have on DH performance. In this section the combination of pressure with swipe, pinch and rotate gestures is studied, in order to determine whether the



(a) An inaccurate 5 Second Trial.

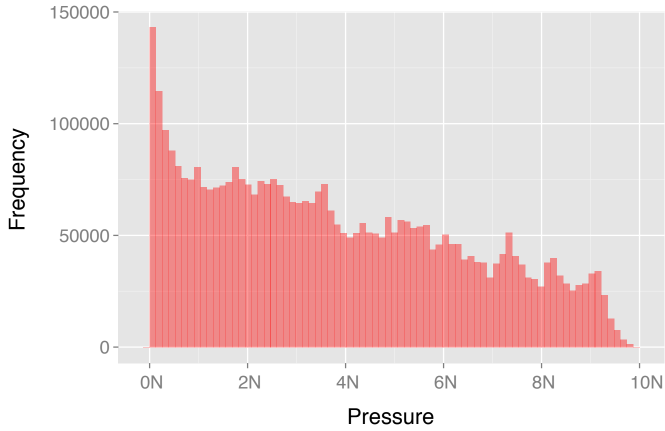


(b) An inaccurate 10 Second Trial.

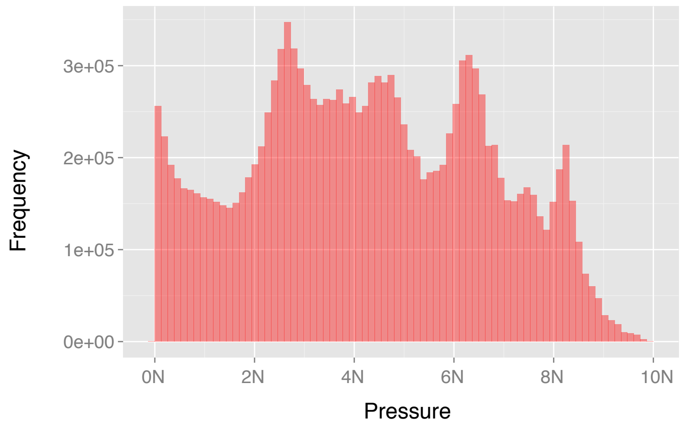


(c) 15 Second Trial demonstrating accurate performance.

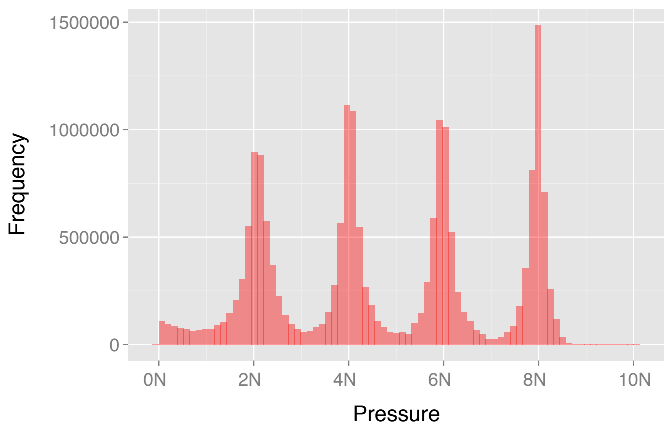
Figure 5.10: A sample of individual traces from 4N Target trials in the Maintain Block.



(a) Targeting Block Pressure Histogram from the Tapping Experiment. Pressure input is skewed towards the lower end of the input range. This would be expected as targets were distributed evenly across the pressure space (and the pressure cursor must be move through the pressure space to reach a target).



(b) Moving Block Histogram from the Tapping Experiment. Pressure input is concentrated around the centre of the pressure space, where the bidirectional targeting mostly took place.



(c) Maintaining Block Histogram from the Tapping Experiment. Pressure input is concentrated around the four pressure targets. Participants were able to maintain pressure most accurately at 8N, which can be seen in this graph.

Figure 5.11: Histograms showing the distribution of pressure input across the three blocks in the Tapping Experiment.

results still hold.

This section contributes to the same research questions as the previous:

> *RQ3: How accurately can users perform a two-handed combination of pressure and touch input while holding the device?*

However, in this section the bidirectional aspect of targeting that was considered in the previous chapter as **Moving** is not considered. Here, only **Targeting** from zero is considered.

It is also of interest to study the effect of **Maintaining** a constant level of pressure *over time*. Therefore, research question 4 asks:

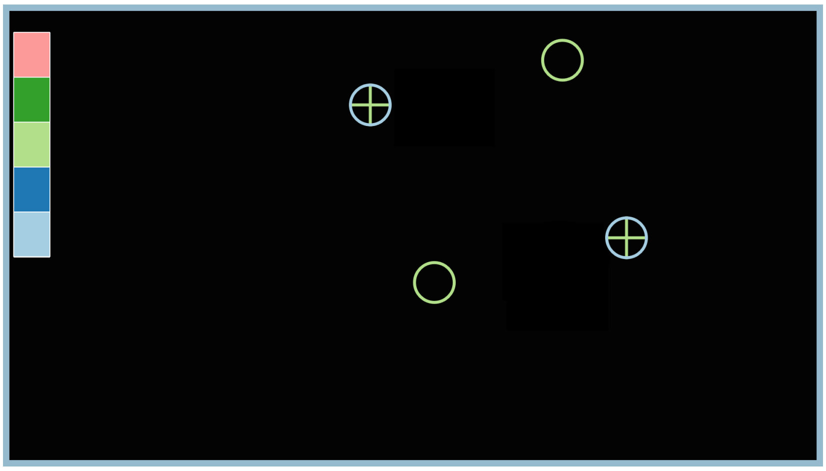
> *RQ4: How accurately can users maintain different levels of pressure during a bimanual interaction?*

Experimental Design

An experiment was carried out to explore the ability to control NDH pressure and DH gesture input, using the same experimental design as the previous section. Across all experimental conditions, participants performed tasks that involved applying pressure with their NDH while performing either a swipe, rotate or pinch gesture on the screen of a tablet device with their DH.

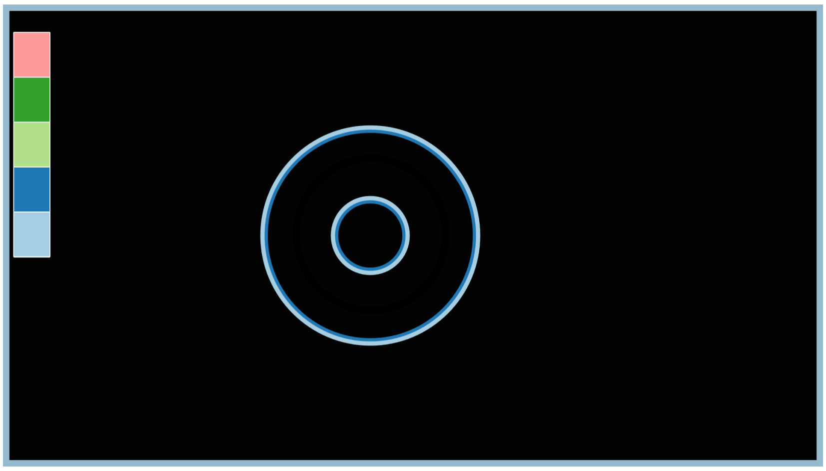
The research questions were evaluated in a single study that consisted of two blocks, each investigating one of the questions outlined above (Targeting and Maintaining), in a single session that took about an hour to complete. Across all blocks, participants controlled pressure using a 'pinch-grip' with their NDH via a force-sensing resistor (FSR) mounted on the bezel of a tablet device while performing a pinch, swipe or rotate gesture on the touchscreen of the device with their DH. Participants supported the tablet with their NDH, resting it on their lap, tilting it towards their face (see Figure 5.13). Across all blocks, the experimental task was adapted from the previous section using an identical hardware setup. Each block required a different method of pressure control, and had a different set of dependent and independent variables, all of which are described in detail below. All pressure values are reported in Newtons (N).

All participants took part in all blocks within one session. The order of the blocks was counterbalanced.



(a)

(b)



(c)

Figure 5.12: Experimental Interfaces from Experiment 6 showing (from top to bottom) Rotate, Swipe and Pinch gestures. Pressure menu is on the left hand side and gesture targets on the right.

Figure 5.13: Participant setup for Experiment 6. Pressure input is controlled via an FSR under the thumb of his non-dominant hand (left-hand), while he holds the tablet as it rests on his lap. Gestures are performed on the screen using his dominant hand.

Participants

Eighteen new participants, (7 Female, 11 Male) aged between 18-30 years old (M=22.5, SD=3.6) took part from the study, 9 of whom were tablet users, none of whom suffered from colour blindness and all were right handed. Participants were paid £6 for participation.

5.3.1 Gestures

Three types of gesture were used: swipe, pinch and rotate. For each type, the size and direction were varied to give a realistic sample of the kind of gestures people perform on touchscreen tablets. Gesture specific details are given below. The location on the screen where the gesture should be performed was also varied. A 3x3 grid of anchor points around the centre of the screen was used to define the location of the gesture. Vertical and horizontal swipe gestures, expand and contract pinch gestures, and clockwise and anti-clockwise rotate gestures were included. Table 5.3 shows the the gesture parameters used in the study and Figure 5.12 shows the visual appearance of each gesture. No visual feedback was given for participants as they completed the gestures.

Swipe	**Distance** 3cm, 7cm	**Direction** Up, Down, Left, Right
Pinch	**Start/End Diameter** 6cm/2cm, 9cm/6cm 9cm/2cm	**Direction** Contract
	2cm/9cm, 2cm/6cm 6cm/9cm	Expand
Rotate	**Distance** (Between Fingers) 8cm	**Direction** Clockwise/Anti-Clockwise (120 °)/(60 °)

Table 5.3: Overview of the Dominant Hand Gestures used in Experiment 6.

Since the focus of the study was not how the specific gesture parameters affect gestural input, but how pressure control affects a representational sample of gestural input and *vice versa*, these gesture parameters were not explicitly controlled. Instead, the number of each gesture performed in a condition was controlled (so the same number of swipes, pinches and rotates were performed in each trial) and the specific gesture parameters were sampled randomly.

For swipe gestures, two lines (spanning the width or height of the screen, for vertical or horizontal swipes, respectively) appeared on the display and participants were asked to swipe from one line to the next. The lines were either vertical or horizontal and were either 3 or 7 cm apart. For pinch gestures, two concentric circles appeared on the display showing the start and end position of the pinch gesture and participants were asked to place their thumb and index finger on the circumference of one circle and perform a pinch gesture to the circumference of the other circle. Start and End Diameter defines how big the two circles are and Direction define whether it is an expand or contract gesture. Three circle Diameters were used (2cm, 6cm and 9cm) and all combinations were used to create three expand and three contract gestures of varying sizes.

For both the swipe and pinch gestures an on screen animation indicated in which direction the participant should perform the gesture. Participants were free to perform the swipe and pinch gestures from anywhere on the start line or start circle since the absolute angle of a pinch or position of a swipe gesture is not always important (for example pinch-to-zoom on a Map application, swipe to turn the page on an e-reader application, or swipe-to-scroll on touchscreen lists).

For rotate gestures, four circles appeared on the screen to show the start and end positions for the participants' thumb and index fingers. Rotate gestures started at either 60 or 120 degrees and rotations were 90 degrees. Rotate gestures that started at 60 degrees were anti-clockwise rotations and rotate gestures that started at 120 degrees were clockwise rotations as in [Hoggan *et al.*, 2013].

5.3.2 Targeting

In the Targeting block, the experimental task (the same as that from Experiment 5 in the previous section) involved selecting pressure targets and performing touch gestures. Pressure targets were selected by applying force to the FSR mounted on the bezel of the device, which moved a cursor up and down a linear menu of coloured targets (see Figure 5.12) (applying pressure moved the cursor up, releasing it moved the cursor back down). Across all conditions, touch gestures were selected randomly from a set of standard gestures (see above). Participants were instructed to first navigate to the corresponding colour in the pressure menu and maintain that level of force while they performed either a swipe, pinch or rotate with their DH. This counted as a single selection. Participants performed each pressure selection twice with each gesture. A border around the main screen and borders around the DH gesture targets also provided visual feedback for pressure input - both would change colour to correspond to the pressure cursor's current position in the menu. This meant that participants would not have to rely solely on the visual feedback provided from the menu itself. Participants were instructed to lift their hand from the pressure sensor after each selection to ensure they started each trial at zero.

Variables and Measures

The Independent Variables were *Menu Size* - the number of targets in the pressure menu (0 Item, 5 Items, 7 Items, 10 Items). The 0 item (control) condition acted as a baseline for DH performance. In it, participants only had to perform gestures with their DH, while holding the device: no pressure had to be applied. For the other menu sizes, the pressure space was divided evenly between menu items to create target widths of 2N for the 5 item menu, 1.4N for the 7 item menu and 1N for the 10 item menu.

Since there were an uneven number of targets in the different menu sizes, 4 common *Target Distances* (2N, 4N, 6N, 8N) were used to compare across menu sizes. This meant that not all the items in each menu were selected, though it meant the same number of selections were made in each condition. This approach has been used successfully in previous pressure input studies [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004].

The Dependent Variables were: *Selection Time* - the time it took to perform a complete selection (navigate to a pressure target and then perform a touch gesture) *Pressure Target Accuracy* - whether the correct item was selected in the pressure menu (the (0 item) control condition was not considered in the Pressure Target Accuracy analysis) and *Dominant Hand*

Error Distance - how accurately the DH gesture was performed. For swipe gestures this was measured as the distance from the target line (y-axis distance for vertical swipes and x-axis distance for horizontal swipes); for rotate gestures this was the Euclidean distance of the thumb and index finger touch points from the centres of the thumb and index finger touch target points (using the magnitude of the vector of those two errors), respectively and for pinch gestures this was measured as the Euclidean distance of the thumb and index finger touch points from the closest points on the circumference of the target circle (using the magnitude of the vector of those two errors). *Target Distance* - the 4 common target distances mentioned above (2N, 4N, 6N, 8N) - was considered as an independent variable in the Pressure Target Accuracy analysis, but not in the Selection Time or DH Error Distance analyses, as Target Distance was not applicable to the (0 item) control condition.

There were four conditions, one for each Menu Size, counter balanced using a latin square. The order of the trials within each condition was randomised. In total there were 18 Participants x 4 Menu Sizes x 4 Target Distances x 3 Gestures x 2 Repetitions = 1728 Trials.

Hypothesis

H 11: Pressure targeting will be faster and more accurate in the conditions with fewer Menu Items, measured by lower Selection Times and higher Pressure Target Accuracy.

H 12: Pressure targeting will be faster and more accurate in the conditions with shorter Target Distances, measured by lower Selection Times and higher Pressure Target Accuracy.

H 13: Dominant-hand gesture input will be more accurate in the conditions with fewer Menu Items, measured by lower Dominant Hand Error.

Results

Selection Time

A two-way repeated measures ANOVA on Selection Time revealed a significant main effect for Menu Size $F(3, 51) = 71.018, p < 0.001$ and a significant main effect for Gesture $F(2, 34) = 21.676, p < 0.001$. There was no significant interaction between the two. *Post hoc* pairwise comparisons on Menu Size with Bonferroni correction (adjusted $p = 0.008$) revealed that participants were significantly faster at selecting targets in the Control condition than in all other Menu Size conditions $(p < 0.001)$ and significantly faster in the 5 item and the 7 item conditions than in the 10 item conditions $(p < 0.001)$ (see Figure 5.14). *Post hoc* pairwise comparisons on Gesture with Bonferroni correction (adjusted $p = 0.01$) revealed that participants performed trials involving Pinch and Swipe Gestures significantly faster than trials involving Rotate gestures $(p < 0.001)$ (see Figure 5.14).

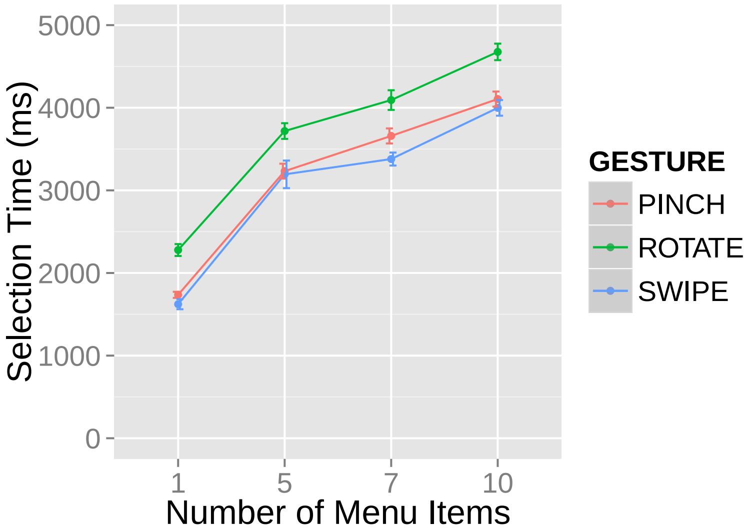


Figure 5.14: Average Selection Time (ms) in the Targeting Condition from Experiment 6.

Pressure Target Accuracy

Overall Pressure Target Accuracy was high (86% - see Table 5.5 and Figure 5.16 for an overview). A three-way repeated measures ANOVA on Pressure Target Accuracy revealed a significant main effect for Menu Size $F(2, 34) = 6.705$, $p < 0.05$, a significant main effect for Gesture $F(2, 34) = 3.848, p < 0.05$ and significant effect for Target Distance $F(3, 51) = 6.650, p < 0.05$. The Menu Size x Target Distance interaction was also significant $F(6, 102) = 2.978, p < 0.05$. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.008$) revealed that participants made significantly more correct pressure selections in the 5 Item menu condition than in the 10 Item menu condition ($p < 0.008$), and significantly more correct pressure selections in trials with the 2N Target Distance than both the 6N and 8N Target Distance ($p < 0.008$). *Post hoc* comparisons for Gesture failed to reach significance. The interaction between Menu Size x Target Distance in terms of pressure accuracy shows that although participants generally made fewer correct selections as both Menu Size and Target Distance increased, performance actually increased in the 7 Item condition for the 8N Target Distance (See Figure 5.17).

Dominant Hand Error

A two-way repeated measures ANOVA on Dominant Hand Error revealed a significant main effect for Menu Size $F(3, 51) = 9.077, p < 0.001$ and a significant main effect for Gesture $F(2, 34) = 341.621, p < 0.001$ (see Figure 5.15). There was no significant interaction between the two. *Post hoc* pairwise comparisons on Menu Size with Bonferroni correction (adjusted $p = 0.008$) revealed that participants performed gestures more accurately in the

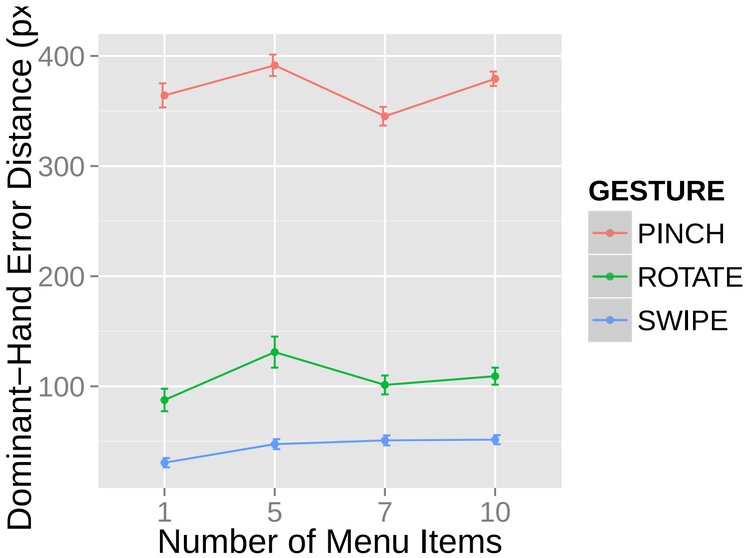


Figure 5.15: Average Dominant Hand Error Distance (px) in the Targeting Condition from Experiment 6.

Menu Size	Selection Time (ms)	DH Error Distance (px)	Pressure Accuracy
5 Items (W = 2N)	2334 *(SD = 415.9)*	27.5 *(SD = 32.5)*	93.6%
7 Items (W = 1.4N)	2520.2 *(SD = 393.9)*	18.8 *(SD = 6.5)*	96.1%
10 Items (W = 1N)	2889.5 *(SD = 612.2)*	25.3 *(SD = 24.7)*	89.3%

Table 5.4: Mean Selection Time, Dominant Hand Target Error Distance and Pressure Accuracy values for each Menu Size in the Targeting Condition. W = Width of the targets in Newtons.

control condition than the ether the 5 Item or 10 Item conditions ($p < 0.008$) and more accurately in the 7 Item condition than the 5 item condition ($p < 0.008$). Participants also performed Swipe gestures most accurately, followed by Rotate then Pinch ($p < 0.001$ between each).

Discussion

Participants were significantly faster in the control condition than any other condition (a result that was also found in the previous section) and they were also significantly more accurate in terms of Dominant Hand Error in the control condition than the 5 Item and 10 Item conditions, suggesting that pressure negatively affects gesture input accuracy (H13). This is contrary to the results observed in the previous study, where there was no evidence

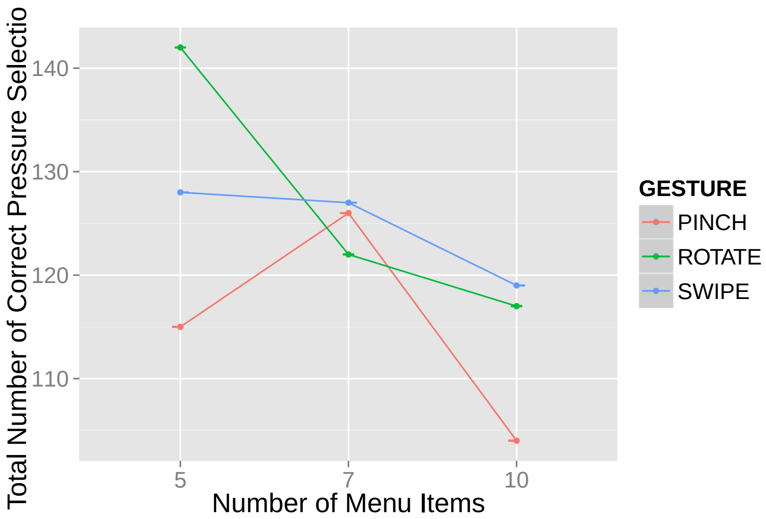


Figure 5.16: Total correct pressure selection across Menu Size and Gesture. Participants made significantly more correct pressure selections in the 5 Item menu condition than in the 10 Item menu condition ($p < 0.008$). *Post hoc* comparisons for Gesture failed to reach significance.

that NDH pressure input affected DH tapping accuracy. In general, Pressure Target Accuracy for each gesture was still high (see Table 5.5) and participants were able to achieve high levels of both pressure and gesture accuracy with Swipe gestures (the simplest gesture in our study) suggesting that the ability to perform a simultaneous combination of pressure and touchscreen gesture input depends on the complexity of the dominant hand action. Figure 5.22a shows a histogram of the pressure input in this block. Comparing this to the equivalent histogram from the targeting block (Figure 5.11a) shows more pressure activity above the 8N target (suggesting that participants overshot that target more in this experiment), which generally suggests a potentially lower level of overall control in this study than the previous.

Participants made significantly more correct selections in the 5 Item condition than the 10 Item condition and made significantly faster selections in the 5 Item and 7 Item conditions than the 10 Item condition, suggesting that larger targets improve performance both in terms of Pressure Target Accuracy and Selection Time (H11). There were significant differences in terms of DH error between all gestures: participants were most accurate for swipe, followed by rotate and then pinch. They were significantly faster at both pinch and swipe than rotate (which might explain rotate's higher accuracy); however, there was no evidence that either Menu Size or Target Distance interacted with Gesture on any measure.

Strangely, participants were significantly more accurate (in terms of DH error) in the 7 Item condition than the 5 Item condition. Pressure accuracy was also about the same in both these conditions. It could be that people perceived the 7 Item condition as harder, and so were more careful during it, which caused performance improvement. This result is difficult to

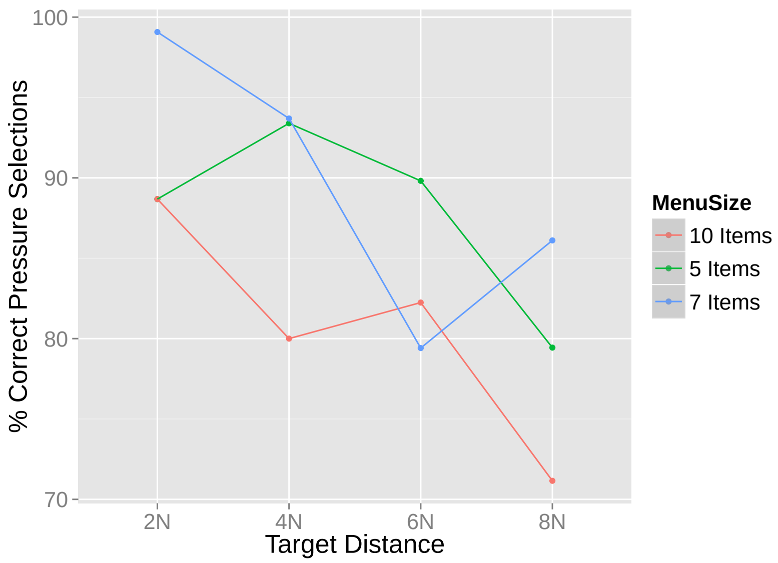


Figure 5.17: Menu Size x Distance Interaction for Pressure Target Accuracy from Experiment 6. Participants were accurate making pressure selections that were closer (2N and 4N away) than ones that were 8N away.

fully explain with the data from this study, and will be left to future work to be explored further.

People were more accurate making pressure selections that were closer (2N and 4N away) than ones that were 8N away, lending support to H12. There was no evidence to suggest that distance affected pressure target accuracy in the Tapping study, suggesting that the complexity of the DH action is an important factor.

5.3.3 Maintaining

This block was designed to assess how accurately users could *maintain a constant level of pressure over time* with their NDH while performing *multiple gestures* with their DH. Within each condition, a trial involved a participant *maintaining* a target pressure for a particular length of time, while performing multiple DH gestures during that time. Participants were instructed to navigate to a particular level of pressure (by applying force and moving the pressure cursor as before) within the pressure space. However, this time the target pressure was indicated by a single red line within the pressure space. Participants had to *maintain* that level of pressure as accurately as possible while performing multiple gestures (selected randomly from the same set used in previous conditions) with their DH until the trial ended. Each trial lasted for either 5, 10, 15 or 20 seconds. Participants would continue to perform DH gestures, while maintaining the target level of pressure, until the trial ended.

Gesture	Control DH Error (px)	Pressure DH Error (px)	Pressure Accuracy(%)
Pinch	363.51 *SD=51.5*	380.2 *SD=47.9*	83.7%
Rotate	93.1 *SD=84.9*	109.5 *SD=82.9*	84.2%
Swipe	31.1 *SD=31.4*	53.2 *SD=39.0*	90.3%

Table 5.5: Increases in Dominant Hand Error Distance from Control to Pressure (average over all pressure conditions) conditions in the Targeting block from Experiment 6.

Variables and Measures

The Independent Variables were: *Target Pressure* - the amount of pressure that was to be maintained in the particular condition (2N, 4N, 6N, 8N) and *Maintain Time* - the amount of time for which participants were required to maintain the Target Pressure (5s, 10s, 15s, 20s).

The Dependent Variables were: *Pressure Error* - defined as the difference between geometric mean of all the sampled pressure values within a trial and the Target Pressure - this allowed us to asses how close to the Target Pressure participants were during the trial; *Pressure Variance* - the variance of all the sampled pressure values within a trial - this allowed us to assess by how much participants deviated from the Target Pressure during the trial; *Target Selection Time* - the time it took participants to select each dominant hand target within a trial - and *Dominant Hand Error Distance* - how accurately the DH gesture was performed. Both Dominant Hand Error Distance and Target Selection Time allowed us to measure how the different levels of pressure affected DH performance.

There were four conditions, one for each Target Pressure, counterbalanced using a latin square. The order of the Maintain Times and Gestures was randomised within each condition. In total there were 18 participants x 4 Target Pressures x 4 Maintain Times x 2 Repetitions = 576 Trials.

Hypothesis

H 14: Pressure Accuracy will decrease as Maintain Time increases, measured as high Pressure Error and High Pressure Variance.

H 15: Pressure Accuracy will decrease as Target Distance increases, measured as high Pressure Error and High Pressure Variance.

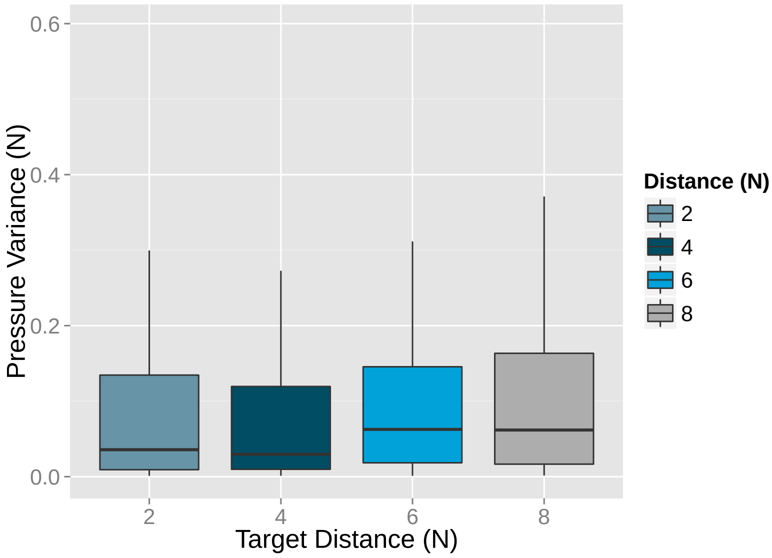


Figure 5.18: Uncapped Pressure Variance for the Maintaining condition from Experiment 6. Pressure Variance in the 2N target distance condition was significantly lower than the 4N and 6N conditions.

H 16: Dominant-hand gesture input will be more accurate in the trials with shorter Maintain Times, measured by lower Dominant Hand Error and faster Gesture Selection Times.

Results

Dominant Hand Error

A three-way repeated measures ANOVA on Dominant Hand Error showed a significant main effect for Gesture, $F(2, 18) = 238.016, p < 0.001$. There was no significant effect for Target Pressure or Maintain Time and no significant interactions. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.01$) revealed that participants performed Swipe gestures most accurately, followed by Rotate gestures, followed by Pinch ($p < 0.001$ between each).

Gesture Selection Time

A three-way repeated measures ANOVA on Gesture Selection Time showed a significant main effect for Gesture, $F(2, 18) = 11.195, p < 0.05$ and a significant main effect for Maintain Time $F(3, 27) = 8.166, p < 0.001$. There was no significant effect for Target Pressure and no significant interactions. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.01$) revealed that participants performed Pinch and Swipe gestures significantly faster than Rotate gestures ($p < 0.01$) and that participants performed gestures

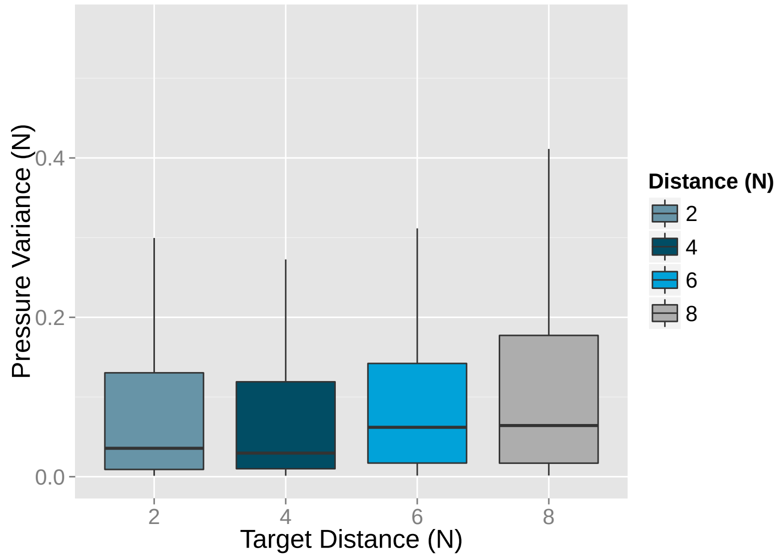


Figure 5.19: Capped Pressure Variance for the Maintaining condition from Experiment 6. Capped Pressure Variance was significantly lower in the 2N target distance condition than the 8N condition.

significantly faster (adjusted $p = 0.008$) in the 20s trials than both the 5s and 10s trials $(p < 0.008)$.

Pressure Error

A two-way repeated measures ANOVA on Pressure Error showed a significant main effect for Target Pressure, $F(3, 51) = 5.163, p < 0.05$. There was no significant effect for Maintain Time and no significant interaction between the two. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.008$) revealed that participants had significantly lower Pressure Error in the 2N target distance condition than the 6N condition($p < 0.008$).

Pressure Variance

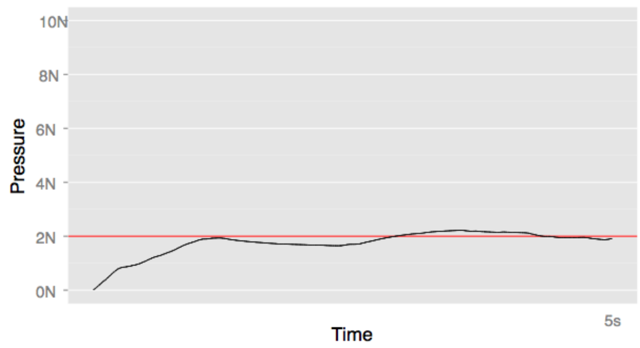
A two-way repeated measures ANOVA on Pressure Variance showed a significant main effect for Target Pressure, $F(3, 51) = 6.273, p < 0.05$. There was no significant effect for Maintain Time and no significant interaction between the two. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.008$) revealed that participants had significantly lower Pressure Variance in the 2N target distance condition than the 4N $(p < 0.008)$ and 6N $(p < 0.008)$ conditions.

Participants had more space in which to vary pressure input in the trials that involved a larger target pressure: for instance, in the 8N target pressure conditions *pressure slips* (inadvertent releases of pressure) could happen over a larger range than in the lower pressure target conditions (an example of frequent pressure slips can be seen in Figure 5.20b). Therefore, it is conceivable that we would observe higher pressure variance from pressure slips in the higher pressure target conditions than the smaller ones. In order to test whether higher pressure variances in the higher target pressures were exaggerated by the fact that participants had a smaller space in which we could measure pressure slips in the lower pressure target conditions, the pressure variance data was analysed capping the variance range to +/-2N around the pressure target. A two-way repeated measures ANOVA on capped Pressure Variance still showed a significant main effect for Target Pressure, $F(3, 51) = 6.404, p < 0.05$, and there was no significant effect for Maintain Time and no significant interaction between the two. *Post hoc* pairwise comparisons with Bonferroni correction (adjusted $p = 0.008$) revealed that participants had significantly lower Pressure Variance in the 2N target distance condition than the 8N condition ($p < 0.008$).

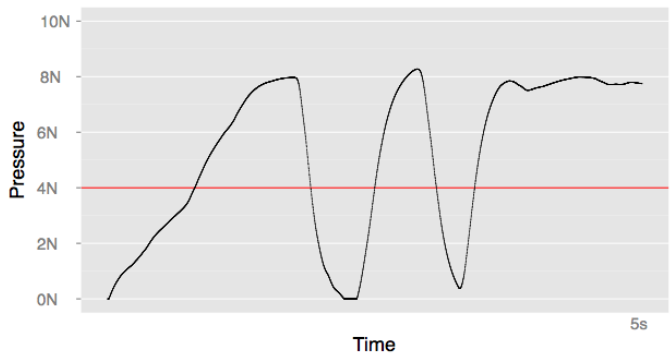
Discussion

Figure 5.18 shows Pressure Variance by Target Distance and Figure 5.19 shows Pressure Variance capped to +/-2N around the target. In general, participants maintained pressure more accurately at lower pressure targets than higher pressure targets (H15). Even controlling for the increased space for pressure slips that is possible at higher pressure targets, participants still exhibited significantly more pressure variance while maintaining pressure at 8N than 2N. Figure 5.22b shows a histogram of the pressure input in Maintaining block. It can be seen that pressure input is more narrowly concentrated around the 2N target than the others. This was in contrast to the results found in Section 5.2.3, where participants were more accurate at maintaining pressure at higher levels of pressure when performing dominant-hand *taps*, suggesting that the addition of a more complex dominant hand task has a strong negative influence on the ability to accurately maintain pressure. However, there was no evidence that maintaining pressure at a higher level affected gestural accuracy.

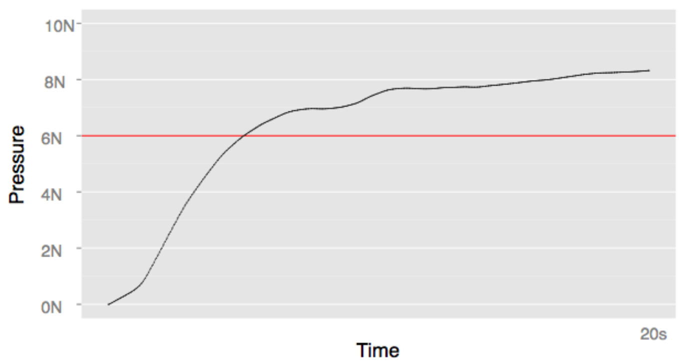
Despite the significant differences in Pressure Variance, the Pressure Error values for each target distance were relatively small (see Figure 5.21). In this block, participants were asked to maintain a constant level of force at a target represented by a single red line. If a 2N target size is assumed, then all of the pressure error that we see in Figure 5.21 falls within the target. Thus, since the Pressure Error was low, but Pressure Variance was high, we can add weight to the claim that that much of the variance came from infrequent large *pressure slips*, rather than frequent small deviations from the target. A simple low-pass filter was used to remove noise from the raw sensor values and selected a cut-off frequency to balance smooth and responsive operation. A potential solution to the high observed Pressure Variance could be to bias this cut-off frequency towards smooth operation, which may reduce the impact



(a) 5 Second Trial demonstrating relatively accurate performance.



(b) An inaccurate 5 Second Trial demonstrating frequent pressure slips.



(c) 20 Second Trial demonstrating relatively stable, but inaccurate, performance.

Figure 5.20: A sample of individual traces from trials in the Maintain Block.

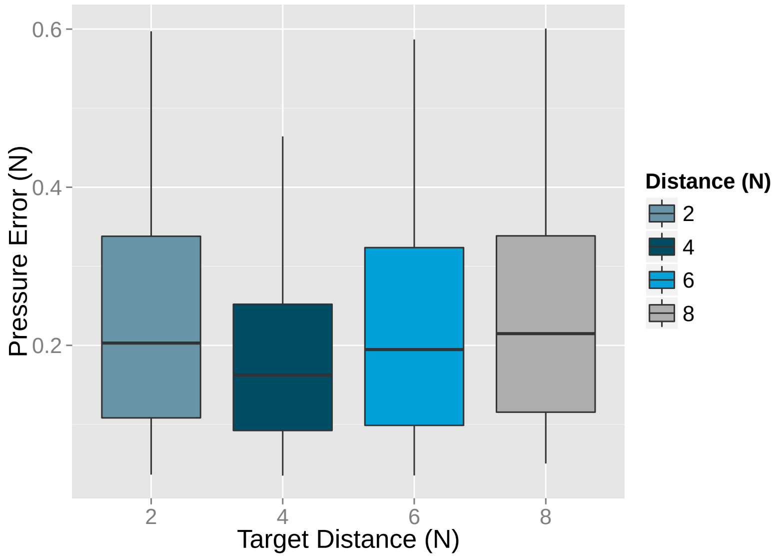


Figure 5.21: Pressure Error across Target Distances from the Maintaining block from Experiment 6. Participants had significantly lower Pressure Error in the 2N target distance condition than the 6N condition.

of the infrequent large *pressure slips*. However, with this there would be an obvious speed-accuracy trade-off to consider. There was no evidence to support H14, that longer maintain times would lead to lower Pressure Accuracy.

The fact that participants took longer to perform Rotate gestures than either Pinch or Swipe gestures and were most accurate when performing Swipe gestures, followed by Rotate then Pinch, is consistent with the results from the Targeting block. Interestingly, participants performed gestures significantly faster in trials with longer maintain times, contradicting H16, which could suggest that there is a stabilisation period at the beginning of the interaction where participants are still adjusting to the conditions and that, over time, participants can perform gestures faster.

5.3.4 Discussion

Across both blocks, participants were significantly slower when performing Rotate gestures and were most accurate performing Swipe gestures, followed by Rotate gestures then Pinch gestures. There are no existing studies comparing the relative performance of multitouch gestures on touchscreen tablet devices, so it is difficult to place these results in a wider context. Certainly, Hoggan *et al.* [Hoggan *et al.*, 2013] found some Rotate gestures to be cumbersome and slow for users on multitouch tabletops; however, the gestures in their study were designed to push the limits of performance and ergonomics (and the Rotate gestures used in this paper were informed from the results of their study). It is surprising that participants were consistently less accurate when performing Pinch gestures. Our method of controlling pinch gestures, in which we explicitly did not control the angle, may have lead participants to perform the gesture more casually across all conditions, thus leading to higher error overall. This choice was made to avoid placing overly strict criteria on Pinch accuracy (since the absolute accuracy of a pinch gesture is rarely required in current tablet interfaces) and since we do not see extreme differences between Pinches in the control and experimental conditions (see Figures 5.14 and 5.15), we can assume that the measure has sufficient internal validity to assess the affect of pressure on *this particular method* of controlling Pinch gestures. However, more study is required to examine whether the measure has external validity in relation to how people actually perform Pinch gestures on tablet devices.

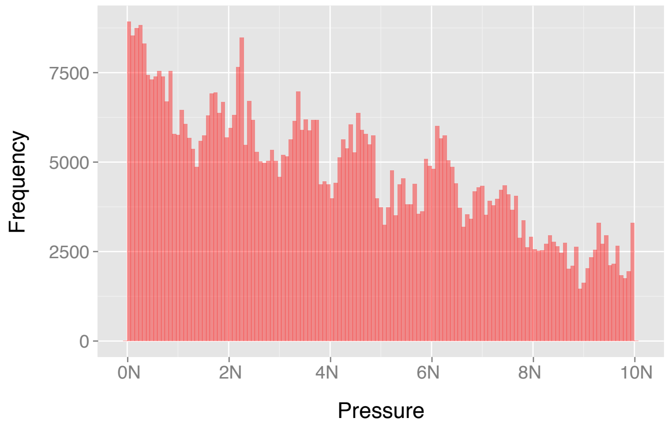
Across both blocks participants were less accurate at selecting pressure targets that were further away. This is in contrast to the results in the previous section, in which there was no evidence for target distance influencing targeting accuracy and in which participants were more accurate at maintaining pressure for larger pressure targets. Therefore, the complexity of the dominant hand action seems to be an important factor affecting accuracy in the higher regions of the pressure space.

However, Pressure Target Accuracy for each gesture was still high (see Table 5.5) and participants were able to achieve high levels of both pressure accuracy and gesture accuracy with Swipe gestures. Furthermore, participants made significantly more correct selections in the 5 Item than the 10 Item menu size condition and made significantly faster selections in the 5 Item and 7 Item menu size conditions than the 10 Item menu size condition suggesting, unsurprisingly, that larger targets improve performance both in terms of Pressure Target Accuracy and Selection Time. This suggests that the ability to perform a simultaneous combination of pressure and touchscreen gesture input is possible, though depends on the size of the pressure target and the complexity of the dominant hand action involved.

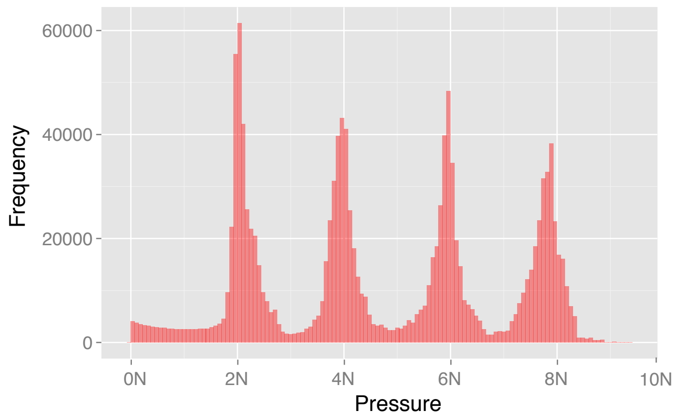
5.4 General Discussion

5.4.1 Pressure Targeting

Across both experiments, Pressure Targeting Accuracy was high: 93.07% for tapping and 86% for gestures. There was no evidence that dominant-hand accuracy was affected by pressure input in the tapping study, however, there was a negative effect on DH gestural accuracy. In terms of bimanual pressure and touch input, it is clear that performance is dependent on the complexity of the DH action involved. We can see this effect when we consider the differences in performance observed in the gesture study. Participants were able to achieve high levels of both pressure accuracy and gesture accuracy with Swipe gestures



(a) Targeting Block Pressure Histogram from the Gesture experiment.



(b) Maintaining Block Histogram from the Gesture experiment. Pressure input is concentrated around the four pressure targets. Participants were able to maintain pressure most accurately at 2N, which can be seen in this graph.

Figure 5.22: Histograms showing the distribution of pressure input across the two blocks in the Gesture experiment.

(the simplest gesture in the studies), but less so with Pinch or Rotate. While all three of these input techniques are clearly gestural, only Pinch and Rotate are multitouch: Swipe is a single touch gesture. Therefore, when DH input techniques are classified into single-touch (tap and swipe) and multitouch (pinch and rotate), it can be seen that single-touch input performed better than multitouch. This is similar to the results observed in [Ng *et al.*, 2015]. Clearly not all single-touch input is less complicated than multitouch input: it would be incorrect to assume that the single-touch input involved in entering text on a gestural keyboard is less complicated than a Pinch or Rotate gesture. So, while it is useful for explaining the differences observed in the results described here, attributing the differences in complexity - and thus performance - to the difference between single-touch and multitouch would be a naive generalisation. However, the evidence does suggest that performance is dependent on the complexity of the dominant hand action involved.

Due to the fact that a different selection mechanism and larger pressure space was used, we cannot directly compare the results of this study with the literature on DH pressure targeting. However, mean Pressure Accuracy for the Targeting block of this study was 93%, which is comparable to the mean pressure accuracy observed by Wilson *et al.* [Wilson *et al.*, 2011] for DH pressure accuracy using the Dwell techniques (98.3% for up to 10 levels of pressure in a 4N pressure space). Whether NDH pressure targeting would be as accurate with a smaller pressure space is unclear. Guiard [Guiard, 1987] argues that the granularity of action of the NDH is coarser than that of the DH, which would suggest a larger pressure space for NDH pressure input might be more appropriate.

Bidirectional Movement

Participants could accurately select targets by *releasing* pressure as well as by *applying* pressure from a non-zero starting point. Bidirectional movement was not evaluated with gestures, so these results are limited to cases where selections are performed by tapping on the touchscreen. However, since previous work [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004] has typically evaluated the precision of applied pressure from a zero-pressure starting point, this result still provides two novel contributions. Firstly, the mean pressure accuracy for the Up selections was 94.9%, demonstrating that *applying* pressure from a non-zero starting point is as accurate as doing so from a zero-starting point. Secondly, this study also demonstrated that participants could select targets accurately by *releasing* pressure: mean pressure accuracy for the Down selections in the Moving block was 89%. While overall accuracy for Down selection was still high, they were significantly slower than Up selections suggesting that, overall, they were not as easy to perform. However, in more general terms, this provides support for the goal of operationalising both the release and application of pressure. This was important as the *release* of pressure can constitute a reversal of an action, which would allow designers to exploit the natural inverse of pressure input. This provides some initial evidence to show that people could target effectively using the natural inverse in a continous manner, without the need to return to the non-pressure state in order to select a new target.

5.4.2 Maintaining Pressure

The results for the Maintaining blocks are a little more complicated as opposite patterns have emerged. In the tapping study, participants were more accurate at maintaining pressure in the higher levels of the pressure space (8N targets) than in the lower levels (2N and 4N targets). However, in the gesture study participants were more accurate at maintaining pressure in the lower levels of the pressure space than the higher. Figures 5.23 and 5.24 show that Pressure Error and Pressure Variance generally increase with Target Distance in the gesture study, while the opposite is true in the tapping study. Overall pressure error was lower in tapping study than the gesture study, though if we assume a 2N target size (a reasonable target size used in the Targeting experiments in this chapter) all the error we see across both experiments falls within the target, which is promising.

Participants performed Swipe gestures more accurately than either Rotate or Pinch gestures, a results also found in the targeting block and further evidence the effect of pressure input is dependent on the complexity of the dominant-hand action involved. Though there was no evidence to suggest that simpler DH gestures resulted in lower pressure error or pressure variance. So while DH accuracy is certainly more accurate with simpler gestures, that cannot be said about the ability to maintain pressure accurately over time.

5.5 Limitations

5.5.1 Selection Times

Comparing the time taken to complete a single DH tap to the time taken to complete a single NDH pressure selection, reveals that multiple taps could be completed in the time taken to complete a single pressure selection (one tap $=\sim 650ms$, while one pressure selection $=\sim 2.3 - 2.9s$), raising questions about the efficiency of pressure as an additional input modality. The goal of this study was not to test whether pressure is more efficient compared to other modalities, but rather to characterise the ability people have to control it using the NDH. While it is true that pressure may be slower, it could enable actions that are easily reversible, simply by reducing the amount of force that was just applied: a property that may be valuable in interaction design. Furthermore, pressure was providing continuous input, as

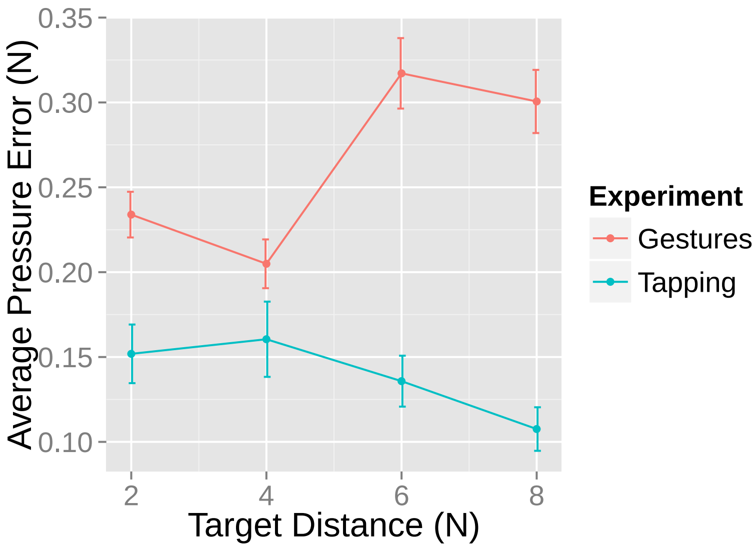


Figure 5.23: Pressure Error across both the Tapping and Gesture Experiments (Experiments 5 & 6). Pressure Error was lower in Tapping study than the Gesture study. However, if we assume a 2N target size (a reasonable target size used in the Targeting experiments in this chapter) all the error we see across both experiments falls within the target.

opposed to the discrete input that would be provided by taps, which makes them difficult to compare directly.

The results from Chapters 3 and 4 demonstrated that the use of pressure as part of a bimanual scrolling interaction technique provided little benefit over existing unimanual scrolling techniques. The goal of this chapter was to characterise the precision of applied pressure within the context of bimanual interaction techniques. The results could be used to inform the design of interacton techniques that complemented, rather than replaced, existing unimanual techniques. The results from this chapter have documented the effect of NDH pressure input on DH touch input and *vice versa*, though little has been said about the role that pressure could play in real applications. In the following sections a set of design guidelines and a number of example applications are presented, which are grounded in the results presented here and aim to illuminate how pressure may be used as part of a bimanual interaction technique on a touchscreen tablet device.

5.6 Design Guidelines

Make the 'no pressure' state the default interface state - As this is the state that will always be returned to when a user relinquishes control of pressure, make it the default state. All non-zero pressure states should be transient in some way, by modifying or adding to the default state of the interface.

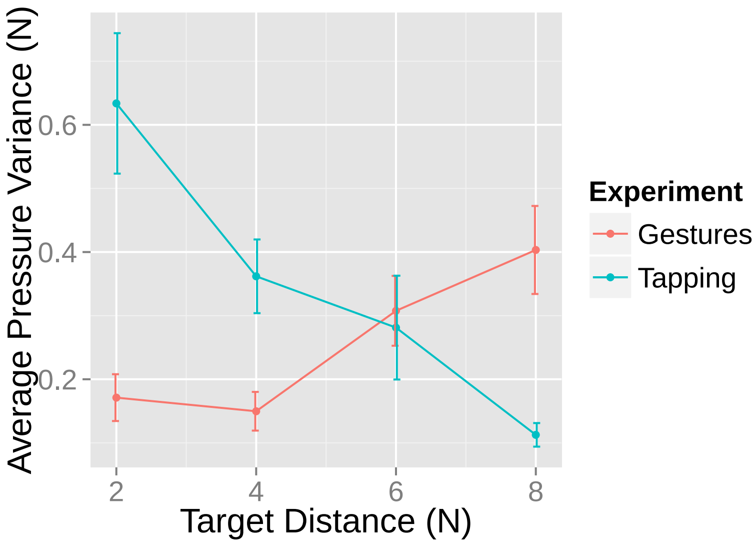


Figure 5.24: Pressure Variance across both the Tapping and Gesture Experiments (Experiments 5 & 6). Pressure Variance generally increases with Target Distance in the Gesture study, while the opposite is true in the Tapping studies.

Middle pressure states should be transitional - Users were able to target items in the mid-low pressure range accurately, both when applying and releasing pressure. However, they were less stable when maintaining pressure at these levels. The results suggest that users are more accurate at maintaining pressure in the lower regions of the pressure space with gestures and more accurate in the higher regions of the pressure space with taps. Therefore, content in these states should be *transitional*. Users can easily move back and forward through these states, by applying and releasing pressure, though users should not have to linger in these states for too long.

Distribute key content - content that users may wish to linger on - between the default no pressure state and higher pressure states - Since users can maintain pressure more stably at high pressure than the mid-to-lower levels, keep key content here. Since the ability to maintain pressure becomes more stable as the amount of pressure increases, the amount of content can increase with pressure. However, precise gestural input should be avoided in the high pressure states.

Precise gestural input should not be required in non-zero pressure states - While overall pressure targeting accuracy was high across all gestures, pressure input negatively affected gestural accuracy. Therefore, *precise* gestural input should be avoided in non-zero pressure states. The absolute accuracy of a touch gesture is not always required in current touchscreen interfaces. For instance, when swiping up and down a list or pinching to zoom in and out of a map, pixel level accuracy is not always necessary and simultaneous pressure and gesture input may be possible in these scenarios. However, with more precise tasks that involve gestures - such as image cropping, or text highlighting - simultaneous pressure and gesture input should be avoided.

The effect of pressure input is gesture dependent - Across both blocks, participants were faster and more accurate - in terms of both gesture and pressure targeting accuracy - with Swipe, than with Pinch or Rotate. For Swipe, dominant-hand error was low and pressure target accuracy was high. Therefore, interfaces that require pressure input can make liberal use of both Swipe and Tap input, though should be more conservative with Pinch and Rotate.

5.7 Example Applications

A number of example applications are described to illustrate the ways in which bimanual pressure and gesture input could be used to create interaction techniques for touchscreen tablet devices.

5.7.1 Weather Application

An example application that uses transient pressure input is a weather application. When the application loads, the current weather is displayed using standard weather icons. Users can move through the forecast for the next few hours by applying pressure. When they reach the highest pressure state, a daily overview is displayed along with a weekly forecast. When control of pressure is relinquished, the application moves back through the hourly forecasts and returns to display the current weather.

The application is simple, but neatly demonstrates the design principles. Being time-series data, the forecast for the next few hours is well suited to the low-mid range pressure values. Users can easily navigate between these levels to get an overview of the weather for the rest of the day, through a simple graphic, without having to linger on any of the states for too long. The high-pressure state provides more detailed information about the forecast, on which users can linger. The default state is the current weather forecast, and by forcing the application to return to it when the user disengages, the application is always in the default state when the user returns.

The application could be extended to include DH action by including multiple locations in a scrollable list. As users scroll through the list of locations using their DH, the current weather for each location is displayed. By applying pressure with their NDH, users can move though the hourly forecast as before: the global context set by the NDH (in this case the time-of-day) would be reflected in each of the locations in the scrollable list. When the highest pressure state is reached, a daily overview is displayed for each location. Users can scroll the list and apply pressure at the same time in order to navigate the forecasts for multiple locations.

5.7.2 Side Menus

Tablet devices, and other touchscreen interfaces, commonly employ a *side menu* widget whereby a menu slides in from the side of the screen from which content can be selected to be displayed in the main viewport. This is common in Apple's iOS Mail application, Facebook's App, in note taking apps like Evernote and versions of it exist on shopping apps and websites such as Amazon. Typically, these menus are overlays on the main content and are designed to be dismissed shortly after a selection is made (in some cases this happens automatically), though others occupy a more permanent position on the screen. In the case of side menus, we can imagine that applying and releasing pressure could move the menu in and out, while the dominant hand scrolls the content of the menu and makes a selection. The result would be a menu that is only open when it is needed, allowing the main viewport to occupy the entire screen to display the main content, and a technique for opening and closing the menu that has a clear and simple method of reversal. Of course, this method would complement, rather than simply replace, existing techniques that can be used to open the menu, so as not to remove the possibility of one handed operation.

5.7.3 Touchscreen Keyboards

A similar technique could be used on a touchscreen keyboard to navigate between different icon and character sets. For instance, on most touchscreen keyboards an increasingly long collections of emojis (small images or icons used to express an ideas or emotions) are available. Pressure could be used to switch between the normal keyboard layout and the emoji collections. Doing so would allow the non-dominant hand to seamlessly switch between the keyboards, while allowing the dominant hand to scroll through and select an emoji. By using more of the pressure space, the non-dominant hand could also switch between the different keyboard character sets, access to which are normally provided through the *shift* key.

5.7.4 Map Application

McGookin *et al.* [McGookin *et al.*, 2011] investigated the use of transparency in map exploration, whereby the transparency of an overlay on a map (in this case an image of a point-of-interest (POI)) could be controlled in order to view both the picture and the map at the same time, with varying degrees of transparency available. In their system, the transparency could be controlled manually by moving a scroll ball on the phone or automatically by the system, though the manual control was more popular with participants. Transient pressure could be used for this application, with more pressure showing more of the POI, and has the potential benefit of forcing the system to return to the map when the user disengages (since the map is the key element of the interface). With respect to the results in the Maintaining condition, users were able to maintain pressure more accurately at higher levels and so would be able to examine the POI image in detail when needed, though still be able to control the degrees of transparency in-between while simultaneously interacting with the map.

This may also be useful in journey or holiday planning tasks where other map overlays could be controlled in a similar way. Moving between a satellite or street view and map view could, for instance, enable users to seamlessly browse a map using different views. Similarly, points-of-interest could be gradually inverted from popular tourist destinations to local favourites, or moving between daytime and nighttime destinations, allowing users to browse a map from different perspectives. Using an auxiliary modality to carry out functions like these is beneficial as it leaves the DH free to manipulate the map, in a way that can allow users to carry out both actions simultaneously.

Crucially, in all these scenarios, the information that is displayed at the extremes (No pressure or High Pressure) is more likely to be viewed for a sustained period of time, while the information in-between is *transitional*.

5.7.5 FineTuner: Media Navigation

FineTuner [Boland *et al.*, 2013] is an engagement dependent music browsing system that allows users vary to the amount of control they have when selecting music. A popular music retrieval interface (Spotify) was augmented with a semantic zooming view of a simple linear music space, enabling both casual and engaged forms of interaction giving users varying degrees of control over the selection of music (see Figure 5.25).

Users can make broad and uncertain general selections to casually describe the mood of the music they want to listen to (see Figure 5.25a). However, they can also exert more control over the system and force it to play a specific song (see Figure 5.25d). As they navigate through the collection by swiping left and right, applying less pressure enables broader selections and allows the system to become more autonomous in making inferences about what the user wants to listen to; as more pressure is applied, the user gains control over the system until eventually specific selections become possible.

FineTuner provides a good example of *transitional* states. The various states of diminished control are accessible using the low-mid range pressure states, though fully casual and fully engaged control are pushed to the default and high pressure state. This means that users can browse their entire music collection by maintaining a high level of pressure, though still access all the diminished control states effectively.

Using FineTuner to browse an entire music collection, song by song, requires a user to maintain full pressure, whereas relinquishing all control to the system requires no pressure.

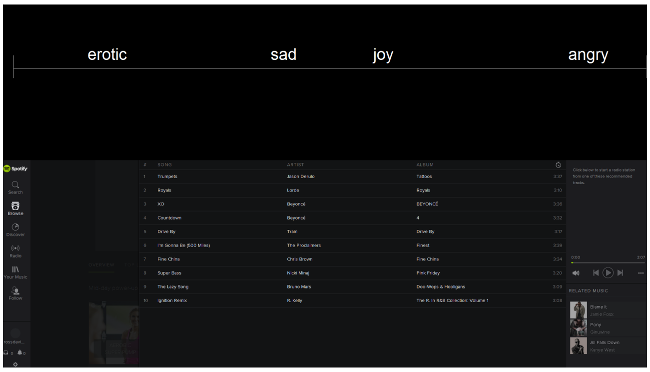
This mapping of force to engagement uses a ‘more pressure = more control’ metaphor, though it also conforms well to the results presented here - users were able to maintain pressure more accurately at higher levels and so would be able to provide the input necessary to select a specific song, as well as to take advantage of the casual nature of the interaction.

5.8 Limitations of the Design Guidelines

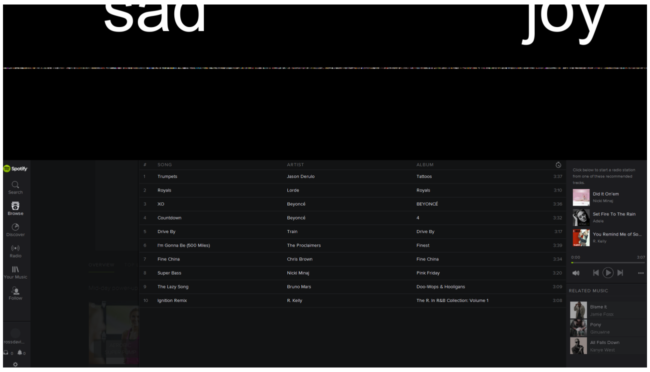
The guidelines and example applications are intended to illustrate opportunities for designing bimanual input techniques for tablet devices based on both the experimental results and the concept of transience. For example, the second guideline “Middle pressure states should be transitional” emerged from the result that people were less accurate when maintaining pressure in the middle pressure states and from the concept of transience because states that users should not have to linger on for too long are, in effect, transient states (they have to be reversed).

However, the fact that users cannot linger on these states for long could be rectified by using a different pressure mapping that would targeting easier, thus removing the need for the guideline. For instance, using a fish-eye technique [Shi *et al.*, 2008] would make it easier to target and maintain pressure in these states, potentially solving the performance issues observed in the experimental results. Though the higher level interaction principle of a ‘transitional state’ is not necessarily a feature that is solely compensating for poor performance. For example the ‘transitional’ aspects in the example applications - such as the movement through time-series data in the weather application or the transition between the map and the semi-transparent overlay in the map application - highlight the distinct character of a ‘transitional state’, demonstrating that the guidelines allow us to think about different kind of interactions that may have been less apparent if conventional targeting was the goal. Thus, since the guidelines are rooted in *both* the experimental results and the concept of transience, they can be used inform novel designs while still allowing for basic pressure input performance to be improved.

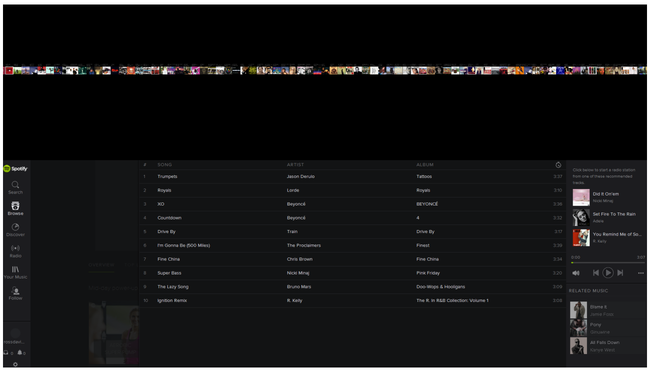
The third guideline - Distribute key content between the default no pressure state and the higher pressure states - also has advantages independent of the experimental results on which it is based. Having ‘key content’ available through the last pressure target has a clear Fitts’ Law advantage (since it has an infinite effective width), therefore users can access content in this part of the pressure space with minimal targeting effort. This would still be a good guideline even if targeting and maintaining performance could be improved throughout the pressure space, in much the same way as the the Taskbar on Windows or the Menubar on Mac OS X have a clear Fitts’ Law advantage regardless of improvement to mouse pointing techniques.



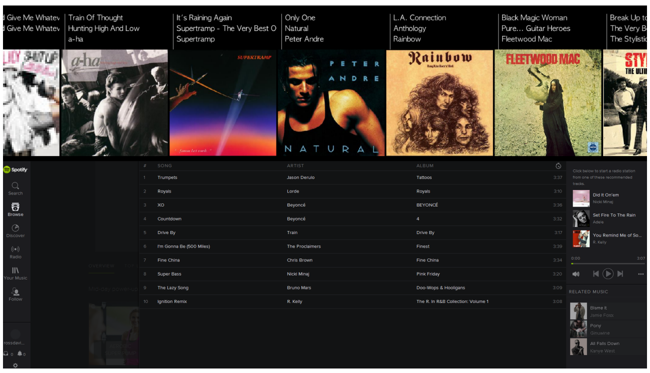
(a)



(b)



(c)



(d)

Figure 5.25: FineTuner [Boland *et al.*, 2013] is an engagement dependent music browsing system that allows users vary to the amount of control they have when selecting music. From top to bottom, the transition between fully casual and fully engaged browsing can be seen. Movement between these states is controlled using NDH pressure, while left to right navigation and selections are controll by the DH on the touchscreen.

The guidelines that reference inaccuracy in pressure targeting with gestural input are purely compensatory and based solely on the experimental results. Techniques that could improve pressure targeting performance (such as the Fish Eye technique discussed above) may make these guidelines redundant. Though, given the added complexity of performing touchscreen gestural input over simple touchscreen taps, this it is not immediately clear that these guidelines do not represent a real issue with the combination of pressure and gesture input. Further work will be required to explore this effect.

While these guidelines highlight the beneficial aspects of transience, the concept does have some disadvantages. For example, while the easy reversal of actions has long been a tenet of good interaction design, the *automatic reversal* afforded by transient pressure is not beneficial in all scenarios. There are obvious examples of this. For instance, when performing parameter manipulation in an editing task (such as tweaking parameters on a filter in an image editing suite) having the action be automatically reversed is clearly unhelpful. However, pressure could be a useful input modality for such tasks and performance has been shown to be high for persistent state selections using, for instance, a rate based mapping (as discussed in the literature review). However, such a mapping is unidirectional and requires the user to cycle through the entire pressure space to return to the beginning, or requires two pressure sensors (one to increase the parameter and another to decrease the parameter). In this case, there is a clear advantage for decoupling the selection event from the pressure input, as advocated in this thesis. For argument's sake, assume that the parameter being manipulated is the contrast of an image. A single transient pressure sensor could be used to increase and decrease the contrast level (which direct visual feedback of the changes being made to the image). The 'ebb and flow' of pressure input is useful here to allow the user to continuously adjust the parameter and use his or her eye to determine when it 'looks' correct. When the desired level is reached, the user can make a selection with his or her other hand in another input channel (by clicking a button) and the changes can be applied. Here, the benefits of transient pressure input are preserved and integrated into the interaction. One challenge here that is nto addressed in this thesis is whether the non-dominant hand can perform sufficiently fine grained manipulations to make it work. From a Kinematic Chain Model perspective, it is not clear whether this is possible without sufficient training (the task is more akin to the bimanual coordination involved in playing the piano than chopping a vegetable). Future work can explore the possibility for more detailed non-dominant hand input for expert users.

There are some tasks, however, that could on occasion benefit from transient interaction and in other situations benefit from more stageful transitions. Adjusting the zoom level on a map (or any visual zoom level adjustment task, such as on images or documents) could benefit from both transient manipulation and stageful manipulation. Transient input would be useful to support peeking interaction - where the zoom level adjustment is only required for a short amount of time before it is reversed. E.g. when zooming into a map to check the name of a street, before zoom back out to the original position to view the entire route. This is also true for tab switching tasks, e.g. on a spreadsheet program where tabs could be switched using pressure and peeking behavior could be useful for checking data or figures in another tab, before returning to the original tab to continue working. These interactions could benefit from both stageful transitions (when the zoom level of the map just needs adjusting or the tab on the spreadsheet program just needs changing) or when peeking behavior is required.

There are already good ‘stateful’ input techniques (most input techniques, including touch and mouse input are designed to be stateful) therefore pressures unique affordances may provide a good compliment to the already fairly stateful interaction techniques afforded by many current input technologies.

5.9 Conclusions

Research Question 3 asked:

> *RQ3: How accurate are people at performing a bimanual combination of NDH pressure and DH touch input on tablet devices?*

The results presented in this chapter from *Experiment 5: Dominant-Hand Tapping* showed that participants were highly accurate when selecting pressure targets with their non-dominant hand, while performing tap selections with their dominant-hand. In general, pressure accuracy was high and the impact on dominant-hand targeting was low. The results show that, for a 10N pressure space, overall pressure targeting accuracy was high (93.07%), though pressure targeting was more accurate with bigger pressure targets (2N (93.6%) or 1.4N (96.1%)) than smaller targets (1N (89.3%)). Mean pressure accuracy when selecting targets by releasing pressure was also high (89%) as was selecting targets by applying pressure from a non-zero starting point (94.4%). Suggesting that accurate bidirectional movement is possible using pressure input.

In *Experiment 6: Dominant-Hand Gestures*, pressure targeting accuracy was still high (86%) for more complicated dominant-hand input techniques (swipe, pinch and rotate gestures). The results show that participants were able to achieve high levels of pressure accuracy (90.3%) using DH swipe gestures (the simplest gesture in the study) suggesting that the ability to perform a simultaneous combination of pressure and touchscreen gesture input depends on the complexity of the dominant hand action involved.

In answer to Research Question 3, NDH pressure input is highly accurate for 5, 7 or 10 targets in a 10N pressure as part of a bimanual interaction, where selections are performed on the touchscreen using DH tap gestures. When selections are performed using dominant-hand gestures, NDH pressure targeting accuracy is dependent on the complexity of the DH gesture being performed, but with gestures like *swipe* showing levels of accuracy similar to that of DH *taps*.

> *RQ4: How accurately can people maintain NDH pressure while performing DH touch input on tablet devices?*

In *Experiment 5: Dominant-Hand Tapping*, participants were more accurate at maintaining pressure in the higher levels of the pressure space, in terms of both Pressure Error (see Figure 5.8) and Pressure Variance (see Figure 5.9), than in the lower levels.

In *Experiment 6: Dominant-Hand Gestures*, the opposite trend emerged. Participants were more accurate at maintaining pressure in the lower levels of the pressure space than the higher. The increased space for pressure slips that is possible at higher pressure targets was controlled for, though participants still exhibited significantly more pressure variance while maintaining pressure at 8N than 2N (see Figures 5.18 and 5.19).

It is promising to note that, if a 2N target size is assumed (a target sized used successfully in the PBLT task that was used to answer Research Question 3), then all of the *Pressure Error* that was found in both Experiment 5 & 6 would fall within the target. Therefore, the results suggest that users can accurately maintain pressure within a 2N target during a bimanual interaction. In general, users are more accurate (in terms of Pressure Error) when maintaining pressure while performing dominant-hand *taps* than they are when they are performing dominant-hand *gestures* (see Figure 5.23). Within each of those dominant-hand input types, users are more accurate at maintaining pressure in the lower regions of the pressure space while *tapping* though are more accurate in the higher regions of the pressure space while performing *gestures*, in terms of both Pressure Error and Pressure Variance (see Figures 5.23 and 5.24).

How accurately users can maintain a particular level of pressure is an understudied area in the literature, the closest being the study of dwell times for the Dwell selection technique (typically $\sim$1s) [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004]. In this thesis, much longer times were considered. By exploring how accurately users can maintain pressure over time, we can begin to understand the design space of transient pressure based interactions that would allow pressure to affect the interface for a sustained period of time.

Chapter 6

Discussion and Conclusion

Touchscreen tablet devices present an interesting challenge to interaction designers: they are not quite handheld like their smartphone cousins, though their form factor affords usage away from the desktop and other surfaces. They can accept multitouch input and, by extension, bimanual input; however, a user will often have to dedicate one hand to holding or supporting the device, constraining their ability to interact fully using two hands on the touchscreen. The challenge for designing bimanual interaction techniques for tablet devices is to enable coordinated two-handed input while the user is comfortably holding the device. In this thesis, the use of non-dominant hand isometric force (pressure) input was explored to support interaction design in this context. The following Research Questions have been addressed:

6.1 Research Questions

RQ 1: Can bimanual input techniques improve scrolling performance on tablet devices?

RQ 2: Can novel input modalities (such as pressure) improve performance for bimanual tablet based scrolling interactions?

RQ 3: How accurate are people at performing a bimanual combination of NDH pressure and DH touch input on tablet devices?

RQ 4: How accurately can people maintain NDH pressure while performing DH touch input on tablet devices?

These four questions were addressed through a series of empirical research studies, focusing on the use of pressure as an auxiliary input modality to support bimanual interaction techniques for touchscreen tablet devices. This chapter summaries the work reported on in this thesis. Limitations of the studies presented and potential avenues for future work are discussed, followed by a final summary and the contributions of this thesis.

6.2 Research Question 1

> *Can bimanual input techniques improve scrolling performance on tablet devices?*

Research Question 1 was answered in Chapters 3 and 4. Four bimanual scrolling techniques were evaluated against two *status quo* unimanual scrolling techniques in a controlled linear targeting task and an image browsing task (which resembled the task of browsing through large media collections) to determine whether the bimanual techniques offered any performance or preference advantages. The bimanual techniques were designed with reference to Guiard's Kinematic Chain (KC) model of bimanual action [Guiard, 1987] in such a way that control of scrolling speed and scrolling direction were split across two hands, where the users' NDH controlled scrolling speed while their DH controlled scrolling direction.

In Chapter 3 – which tested the techniques using a controlled linear targeting task – the bimanual techniques generally outperformed equivalent unimanual techniques. The Dial and Slider bimanual technique was superior to the others in terms of Movement Time (see Figure 3.4) and the Dial and Pressure bimanual technique was superior in terms of Subjective Workload (see Figure 3.5). The studies suggest that the bimanual scrolling techniques are better than the *status quo* unimanual techniques in terms of both performance and preference, lending support to the body of evidence in HCI that the KC Model [Guiard, 1987] is a useful tool to inform the design of bimanual interactions that allow people to carry out tasks more effectively than with unimanual equivalents.

However, in Chapter 4 – which tested the same techniques using an image browsing task – there was no evidence to suggest that the bimanual techniques provided any concrete benefits over the unimanual ones. The bimanual techniques outperformed the Unimanual dial technique, however, there was no evidence to suggest that any of the bimanual techniques provided benefit over Unimanual touch. The Unimanual Touch technique is the *status quo* scrolling technique on commercially available touchscreen tablets and smartphones and so the lack of clear benefit over that technique is more important than benefit over the, more novel (in terms of tablet devices) unimanual dial technique. Combining the results of both chapters, the bimanual techniques offer benefits over unimanual equivalents in tasks involving scrolling to and selecting known targets, though these advantages do not translate to more open ended browsing task.

Based on an analysis of personal music listening histories using Last.fm data, Boland *et al.* [Boland *et al.*, 2013] suggest that music listeners exist on a engagement spectrum between *Casual* and *Engaged* based on how much *Control* they take over selections. *Engaged* users have "high initial engagement in the interaction, with more specific retrieval queries, e.g. selecting a particular album. They then make very few further interventions, which are quick and decisive". While *Casual* users "wish to satisfice, investing little effort in the retrieval at any given point. Their lack of initial control means that these users need to be able to easily make corrective interventions". They observe that most users exist somewhere between these two extremes and vary between levels of *Casual* to *Engaged* music listening, depending on their listening context. The bimanual and unimanual techniques might exist to complement each other as a way of supporting different kinds of listening behaviour, where unimanual scrolling exists to support casual browsing of a collection, while the bimanual techniques offer more control when required, complemented perhaps by search functionality for when an exact target is desired.

6.3 Research Question 2

> *Can novel input modalities (such as pressure) improve performance on bimanual tablet based scrolling interactions?*

Research Question 2 was answered in Chapters 3 and 4. Four bimanual scrolling techniques, that used various combinations of pressure, physical dial and touchscreen input, were evaluated using the same controlled linear targeting experiment and image browsing task. The results from Chapter 3 suggest that, for the linear targeting task, the touch slider speed control method resulted in faster performance than the pressure sensor, though participants favoured the dial and pressure sensor technique in terms of subjective workload, implying they found it easier to use. While participants were able to get to the target faster using the touch slider method, over long distances they were more likely to overshoot than with the pressure sensor, which might be the reason why the Dial and Pressure technique was subjectively preferred.

The results from Chapter 3 reveal that, as a direction control method, participants performed tasks faster when using the rear mounted physical dial than when using touchscreen gestures. Repetitive flick and or drag gestures make it difficult to get anything but very coarse control over the scrolling speed and cause the interaction to become slow and staggered. The more continuous scrolling control afforded by the dial might be why it turned out to be faster. However, the results from Chapter 4 suggested that a flat, rear mounted, capacitive dial is not a particularly good modality for browsing though collections of images on its own, or as part of a bimanual technique (the Dial and Slider technique had significantly lower recall than Touch and Pressure, Touch and Slider and Dial and Pressure). The flat, capacitive dial was chosen to replace the physical dial because it was considered to be a more realistic addition to the form factor of a tablet device. This result suggests firstly that the different form factors were not equivalent, did not afford the same levels of control and that the bigger, physical dial was more suitable for rear mounted tablet interaction. However, given the impracticality of using such a dial in reality, it is unlikely that current generation tablet device would benefit by replacing touchscreen gesture input with a physical dial.

The results from Chapter 4 suggest that pressure is a more effective auxiliary modality than the touch slider in the context of bimanual scrolling techniques. Pressure was consistently better across both of the dominant hand modalities, whereas the performance of the touch slider was significantly affected by the dominant hand modality used. Combining the results of both chapters suggests that participants can more easily control a pressure sensor when holding a tablet device than a touch slider as part of a bimanual scrolling technique, which shows that as a novel modality, pressure can improve scrolling performance as part of bimanual tablet based scrolling interactions.

6.4 Research Question 3

> *RQ3: How accurately can users perform a two-handed combination of pressure and touch input while holding the device?*

Research Question 3 was answered in Chapter 5. Two experiments were carried out to evaluate performance in a pressure-based linear targeting (PBLT) task, where pressure input was controlled using the NDH on the bezel of a tablet device and selections were performed using the DH by performing touchscreen *taps* (*Experiment 5: Dominant-Hand Tapping*) and *pinch, swipe* or *rotate* gestures (*Experiment 6: Dominant-Hand Gestures*) on the touchscreen of the device. In *Experiment 5: Dominant-Hand Tapping*, the results showed that, for a 10N pressure space, overall pressure targeting accuracy was high (93.07%), though pressure targeting was more accurate with bigger pressure targets (2N (93.6%) or 1.4N (96.1%)) than smaller targets (1N (89.3%)). Mean pressure accuracy when selecting targets by releasing pressure was also high (89%), as was selecting targets by applying pressure from a non-zero starting point (94.4%). Suggesting that accurate bidirectional movement is possible using pressure input.

In *Experiment 6: Dominant-Hand Gestures*, pressure targeting accuracy was still high (86%) for more complicated dominant-hand input techniques (swipe, pinch and rotate gestures), though that pressure input negatively affects gestural accuracy. The results show that participants were able to achieve high levels of pressure accuracy (90.3%) using DH swipe gestures (the simplest gesture in the study) suggesting that the ability to perform a simultaneous combination of pressure and touchscreen gesture input depends on the complexity of the dominant hand action involved.

Previous work, such as [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004], has evaluated the precision of applied pressure using the DH as part of a unimanual interaction. The results presented here provide a novel perspective on pressure input in HCI by studying the precision of NDH pressure input as part of a bimanual interaction. NDH pressure input is highly accurate for 5, 7 or 10 targets in a 10N pressure as part of a bimanual interaction, where selections are performed on the touchscreen using DH tap gestures. When selections are performed using dominant-hand gestures, NDH pressure targeting accuracy is dependent on the complexity of the DH gesture being performed, but with gestures like *swipe* showing levels of accuracy similar to that of DH *taps*. This work has also shown that bidirectional movement is possible using pressure input by demonstrating that pressure targeting accuracy was high when releasing pressure as was selecting targets by applying pressure from a non-zero starting point.

6.5 Research Question 4

> *RQ4: How accurately can users maintain different levels of pressure during a bimanual interaction?*

Research Question 4 was also answered in Chapter 5. Two experiments were carried out, in which the precision of applied pressure *over time* was evaluated. Participants were asked to navigate to a particular pressure target and maintain that level of force for a set period of time (5, 10, 15 or 20 seconds) while performing dominant-hand taps (*Experiment 5: Dominant-Hand Tapping*) or pinch, swipe or rotate gestures (*Experiment 6: Dominant-Hand Gestures*) on the touchscreen of the device. In *Experiment 1: Dominant-Hand Tapping*, participants were more accurate at maintaining pressure in the higher levels of the pressure space than in the lower levels in terms of both Pressure Error (see Figure 5.8) and in terms of Pressure Variance (see Figure 5.9).

However, in *Experiment 6: Dominant-Hand Gestures* participants were more accurate at maintaining pressure in the lower levels of the pressure space than the higher. Even controlling for the increased space for pressure slips that is possible at higher pressure targets, participants still exhibited significantly more pressure variance while maintaining pressure at 8N than 2N (see Figures 5.18 and 5.19). Therefore, the ability to accurately maintain different levels of pressure during a bimanual interaction is dependent both on the target pressure and the complexity of the dominant-hand action involved.

If a 2N target size is assumed (a target sized used successfully in the PBLT task that was used to answer Research Question 3), then all of the *Pressure Error* that was found in both Experiment 1 & 2 would fall within the target, which is promising. Therefore, to answer Research Question 4, users can accurately maintain pressure within a 2N target during a bimanual interaction. In general, users are more accurate (in terms of Pressure Error) when maintaining pressure while performing dominant-hand *taps* than they are when they are performing dominant-hand *gestures* (see Figure 5.23). Within each of those dominant-hand input types, users are more accurate at maintaining pressure in the lower regions of the pressure space while *tapping* though are more accurate in the higher regions of the pressure space while performing *gestures*, in terms of both Pressure Error and Pressure Variance (see Figures 5.23 and 5.24).

How accurately users can maintain a particular level of pressure is an understudied area in the literature, the closest being the study of dwell times for the Dwell selection technique (typically $\sim$1s) [Wilson *et al.*, 2011, Wilson *et al.*, 2010, Ramos *et al.*, 2004]. Here, much longer times were considered. By exploring how accurately users can maintain pressure over time, we can begin to understand the design space of transient pressure based interactions that would allow pressure to affect the interface for a sustained period of time.

6.6 Contributions

This thesis provides the first detailed study of non-dominant hand pressure input and has demonstrated that it is an effective modality to expand the range of available bimanual input techniques for touchscreen tablet devices. In this context, this thesis has:

- Explored the use of pressure as a speed control modality for bimanual scrolling and demonstrated that pressure is a more effective speed control than a touch slider;
- Quantified the impact of non-dominant hand pressure on existing dominant-hand input techniques (Tap, Swipe, Pinch and Rotate gestures) and *vice versa*;
- Showed that non-dominant hand pressure *Targeting* - by selecting targets from a zero-pressure starting point, and targeting by both applying and releasing pressure from a non-zero starting point - is highly accurate;
- Showed that *Maintaining* pressure over time is also highly accurate where maintaining pressure is more accurate in the higher levels of the pressure space when performing *taps*, and where maintaining pressure is more accurate in the lower levels of the pressure space when performing *gestures*.

- Provided a definition of pressure as a *transient* modality and demonstrated the use of that definition for the design of pressure based interactions.

6.7 Limitations and Future Work

6.7.1 Different Tablet Holds

The studies presented in this thesis investigated the use of pressure as an auxiliarly input modality for tablet devices in the context where users were seated and holding the device in their NDH, supporting the weight of the tablet with their lap. This hold was chosen as the focus of our study as it accurately represents the ways in which people can hold and support a tablet devices while seated in the home. It has been noted that tablet use predominately takes place in home, often while seated on the couch or bed [Müller *et al.*, 2012] and the way in which users were asked to hold the tablet in the experiments described in this thesis is representative of the ways it can be held in those scenarios. However, due to the portability of their form factor, this is not the only context where tablet use can take place and there are many other ways in which a user can hold and support a tablet [Wagner *et al.*, 2012]. Therefore, the applicability of the results presented in this thesis is limited to scenarios where the user is sitting and able to support the device on their lap.

Throughout this thesis, a single force-sensing resistor was placed on the bezel, on the left hand side of the device, which was used for pressure sensing. Many of the tablet holds identified by Wagner *et al.* [Wagner *et al.*, 2012] involved the users NDH coming into contact with the bezel of the device in some way, whether it be on the side using the thumb as in the studies presented here or, for example, from on top using the fingers as they curl round the bezel as they grip the device from underneath. Therefore, a clear avenue for future work would be to replicate the studies describes in this thesis to determine whether the results hold for different tablet holds.

6.7.2 Applications of Transient Pressure

This thesis investigated the use of pressure as both a modality within an interaction technique for a particular application and abstractly, as a functional primitive. A number of example applications were described to motivate the idea of pressure as non-dominant hand input modality and to demonstrate how it could complement, rather than replace, existing touch-screen input techniques. Following up these design suggestions, in terms of evaluation at the application level as well as bottom-up design of what could be called *transient widgets*, would be another avenue for future work. The results from Chapters 3 and 4 suggest that not all instances of bimanual input techniques offer benefits over existing unimanual techniques, and that benefits can be task dependent; and the results from Chapter 5 suggest that pressure input has a negative effect on dominant-hand gestural accuracy. Therefore, a key aspect of future work will be to identify areas where pressure input may complement dominant-hand input and to assess whether the effect it has on DH accuracy (particularly with more complicated DH gestures) is significant in the particular application domain (since inaccuracy when performing a pinch gesture is likely quite different in a map zooming task than it is in a photo-cropping task). There are still many aspects to explore in the design space for non-dominant hand pressure input.

6.7.3 Pressure Filtering

There have been a wide variety of sensor configuration used in the literature, though few report the details of the Analog-to-Digital conversion. It is normal for sensor data to be noisy, and there are many techniques that can be employed to filter out that noise. For instance, Stewart *et al.* [Stewart *et al.*, 2010] report to have used a Savtizky-Golay filter to reduce the noise from their FSR setup. However, it is not common for researchers to report on the filtering process in detail. Researchers have reported the particular hardware used in their experimental setup, such as commercial solutions from Walcom or bespoke solutions involving affixing FSRs to other devices, the different ways in which the pressure space is split or the particular control mappings such as Positional or Rate-based control. In this thesis, a simple low-pass filter was used to convert the raw pressure data into a usable input stream.

A low-pass filter is one of the most simple filters that can be employed to reduce noise from sensor data. It operates by passing signals with a frequency lower than the cutoff frequency and attenuating signals with a frequency higher than the cutoff. Subjectively, in terms of pressure input, this means that filter will smooth the pressure stream, by reducing both noise and any high frequency user input. When the pressure stream is filtered lightly or not at all, control of the pressure sensor will be experienced as responsive or sensitive and when the pressure stream is heavily filtered control of the pressure sensor will be experienced as slow and inflationary. While the cut-off value of the low-pass filter was chosen during pilot testing to subjectively optimise controllability (by maximising smoothness and responsiveness), this value was not experimentally verified and only one value was used throughout. It is possible that a more aggressive filter would have improve both *Targeting* and *Maintaining* accuracy (though, perhaps at the expense of selection time). Therefore, future work could explore the use of different filter configurations in order to improve performance.

6.7.4 Non Tablet Based Pressure Interactions

In this thesis, tablet based pressure interaction was the focus. Current commercially available tablet devices do not support rich forms of bimanual input and for that reason the use of pressure was explored to expand the range of available bimanual input for such devices. However, the basic principle of auxiliary non-dominant hand pressure coupled with some form of primary dominant-hand input could be extended expand the range of bimanual input in different domains. For instance, devices like the Microsoft Kinect enable at a distance gesture based interaction. Such devices allow users to interact with, for instance, large displays where selections and other manipulations are made via mid air gestures. One can imagine a bimanual input strategy for such devices that enable non dominant hand pressure input via a small hand held sensor that can detect when pressure is applied by squeezing on the bezel of an existing hand held device (such as a smartphone) or using a bespoke device that can detect when pressure is applied between the thumb and the knuckle of the index finger of the user's non dominant hand (such as a pressure sensitive ring that is worn on the index finger). Using such a setup, coordinated bimanual input, similar to that described in this thesis, could be achieved while the dominant hand performs mid air gestures. It could be possible, for instance, to build a large screen version of the FineTuner system which is displayed on the television screen in a user's home. Horizontal navigation and selection is achieved via the dominant hand performing mid air swipe and tap gestures in front of the television and where the zooming effect is achieved with NDH pressure input through one of the previously mentioned devices. This would allow the experience of using FineTuner to be translated to different devices in the home, while keeping the same affordances.

6.8 Conclusions

This thesis has investigated the use of pressure as a non-dominant hand input modality for bimanual interaction techniques on touchscreen tablet devices. The ownership of tablets has been on the rise and, despite the portability afforded by the form factor, use predominantly takes place in the home [Ofcom, 2012], often while sitting on the couch or bed [Müller *et al.*, 2012]. A typical small form device, such as a phone, can be held comfortably in the palm of the hand and can often be operated effectively using the thumb of the hand with which it is being held. This is not true for typical tablet devices. The form factor of these devices requires a user to support a larger weight and navigate more screen space. Thus, while the tasks being performed may be similar, the form factor of tablet devices requires either two hands, or a supporting surface, to interact.

Previous work on bimanual HCI has suggested that there are bimanual interaction techniques that offer both manual and cognitive benefits over equivalent unimanual techniques

[Leganchuk *et al.*, 1998]. In this thesis, the use of pressure was explored to expand the design space of bimanual interaction techniques for touchscreen tablet devices. Pressure was chosen because it has been showen to be useful as a primary input modality on mobile devices [Brewster and Hughes, 2009, Wilson *et al.*, 2011, Wilson *et al.*, 2010, Heo and Lee, 2011] and as an augmentation to finger/stylus input on touchscreens [Ramos and Balakrishnan, 2005, Ramos *et al.*, 2004]. It has the property of adding another dimension that can be accessed continuously without large hand movements [Stewart *et al.*, 2010] and can be detected using simple force sensing resistors (FSRs) that are flat and can be added to mobile devices without affecting the form factor.

The research in this thesis has been the first to systematically explore the use of pressure as a non-dominant hand input modality in the context of bimanual interaction techniques and has demonstrated that pressure is a viable candidate for expanding the role of the non-dominant hand when interacting with tablet devices.

Appendices

To save paper, the following appendices are available from `http://www.rossmclachlan.co.uk/appendices`*.* *Each appendix contains experimental documents and raw data.*

A Experimental Files Experiments 1 & 2

B Experimental Files Experiments 3 & 4

C Experimental Files Experiments 5 & 6

Bibliography

[Balakrishnan and Hinckley, 2000] Balakrishnan, R. and Hinckley, K. (2000). Symmetric bimanual interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (ACM CHI '00)*, pages 33–40, The Hague, The Netherlands. ACM.

[Benko *et al.*, 2006] Benko, H., Wilson, A., and Baudisch, P. (2006). Precise selection techniques for multi-touch screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (ACM CHI '06)*, pages 1263–1272, Montréal, Québec, Canada. ACM.

[Bier *et al.*, 1993] Bier, E., Stone, M., Pier, K., Buxton, W., and DeRose, T. D. (1993). Toolglass and magic lenses: the see-through interface. In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '93)*, pages 73–80, Anaheim, CA. ACM.

[Boland *et al.*, 2013] Boland, D., McLachlan, R., and Murray-smith, R. (2013). Engaging with Mobile Music Retrieval. In *To Appear in Proceedings of MobileHCI 2015*, Copenhagen, Denmark. ACM Press.

[Boland *et al.*, 2015] Boland, D., McLachlan, R., and Murray-smith, R. (2015). Engaging with Mobile Music Retrieval. In *Proceedings of the 17th international conference on Human-computer interaction with mobile devices & services (MobileHCI '15)*, Copenhagen, Denmark. ACM.

[Brandl *et al.*, 2008] Brandl, P., Forlines, C., Wigdor, D., Haller, M., and Shen, C. (2008). Combining and measuring the benefits of bimanual pen and direct-touch interaction on horizontal interfaces. In *Proceedings of the working conference on Advanced visual interfaces (AVI '08)*, pages 154–161, Napoli, Italy. ACM.

[Brewster and Hughes, 2009] Brewster, S. and Hughes, M. (2009). Pressure-based text entry for mobile devices. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '09)*, pages 1–4, Bonn, Germany. ACM.

[Buxton and Myers, 1986] Buxton, W. and Myers, B. (1986). A study in two-handed input. In *ACM SIGCHI Bulletin*, volume 17, pages 321–326. ACM.

[Cechanowicz *et al.*, 2007] Cechanowicz, J., Irani, P., and Subramanian, S. (2007). Augmenting the mouse with pressure sensitive input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (ACM CHI '07)*, pages 1385–1394, San Jose, California, USA. ACM.

[Cockburn and Gutwin, 2009] Cockburn, A. and Gutwin, C. (2009). A predictive model of human performance with scrolling and hierarchical lists. *Human–Computer Interaction*, 24(3):273–314.

[Cunningham *et al.*, 2004] Cunningham, S. J., Jones, M., and Jones, S. (2004). Organizing Digital Music for Use: An Examination of Personal Music Collections. In *Fifth International Conference on Music Information Retrieval (ISMIR '04)*, Barcelona, Spain.

[Deselaers *et al.*, 2008] Deselaers, T., Hanbury, A., Viitaniemi, V., Benczúr, A., Brendel, M., Daróczy, B., Balderas, H. J. E., Gevers, T., Gracidas, C. A. H., Hoi, S. C. H., and Others (2008). Overview of the ImageCLEF 2007 Object Retrieval Task. In *Advances in Multilingual and Multimodal Information Retrieval*, pages 445—-471. Springer.

[Dillon *et al.*, 1990] Dillon, R. F., Edey, J. D., and Tombaugh, J. W. (1990). Measuring the true cost of command selection: techniques and results. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '90)*, number April, pages 19–26, Seattle, Washington, USA. ACM.

[Essl *et al.*, 2009] Essl, G., Rohs, M., and Kratz, S. (2009). Squeezing the sandwich: A mobile pressure-sensitive two-sided multi-touch prototype. In *Demonstration at UIST'09*, Victoria, BC, Canada.

[Ghazali and Dix, 2005] Ghazali, M. and Dix, A. (2005). Knowledge of Today for the Design of Tomorrow. In *Proceedings of the 2nd International Design and Engagibility Conference (IDEC '05)*, Edinburgh, Scotland.

[Guiard, 1987] Guiard, Y. (1987). Asymmetric division of labor in human skilled bimanual action: the kinematic chain as a model. *Journal of Motor Behavior*, 19(4):486–517.

[Hart, S. G. & Staveland, 1988] Hart, S. G. & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Human mental workload*.

[Heo and Lee, 2011] Heo, S. and Lee, G. (2011). Force Gestures: Augmenting Touch Screen Gestures with Normal and Tangential Forces. In *Proceedings of the 24th Annual*

ACM Symposium on User Interface Software and Technology (UIST '11), pages 621–626, Santa Barbara, California, USA. ACM.

[Hick, 1952] Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, 4(1):11–26.

[Hoggan *et al.*, 2012] Hoggan, E., Stewart, C., Haverinen, L., Jacucci, G., and Lantz, V. (2012). Pressages : Augmenting Phone Calls with Non-Verbal Messages. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology (UIST '12)*, pages 555–562, Cambridge, Massachusetts, USA. ACM.

[Hoggan *et al.*, 2013] Hoggan, E., Williamson, J., Oulasvirta, A., Nacenta, M., Kristensson, P. O., and Lehtiö, A. (2013). Multi-touch rotation gestures: performance and ergonomics. In *Proceedings of ACM CHI'13*, pages 3047–3050, Paris, France.

[Holman *et al.*, 2013] Holman, D., Hollatz, A., Banerjee, A., and Vertegaal, R. (2013). Unifone: Designing for Auxiliary Finger Input in One-handed Mobile Interactions. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, TEI '13, pages 177–184, New York, NY, USA. ACM.

[Kabbash and Buxton, 1994] Kabbash, P. and Buxton, W. (1994). Two-handed input in a compound task. In *Conference Companion on Human Factors in Computing Systems (CHI '94)*, pages 417–423, Boston, Massachusetts, USA. ACM.

[Kildal and Wilson, 2012] Kildal, J. and Wilson, G. (2012). Feeling It : The Roles of Stiffness , Deformation Range and Feedback in the Control of Deformable UI. In *Proceedings of the 14th ACM International Conference on Multimodal Interaction (ICMI '12)*, pages 393—-400, Santa Monica, California, USA. ACM.

[Kin *et al.*, 2009] Kin, K., Agrawala, M., and DeRose, T. (2009). Determining the benefits of direct-touch, bimanual, and multifinger input on a multitouch workstation. *Proceedings of Graphics Interface 2009*, pages 119–124.

[Kin *et al.*, 2011] Kin, K., Hartmann, B., and Agrawala, M. (2011). Two-handed marking menus for multitouch devices. *ACM Transactions on Computer-Human Interaction*, 18(3):1–23.

[Latulipe, 2006] Latulipe, C. (2006). *A symmetric interaction model for bimanual input*. PhD thesis, University of Waterloo.

[Latulipe *et al.*, 2006] Latulipe, C., Mann, S., Clarke, C. L. A., and Kaplan, C. S. (2006). symSpline : Symmetric Two-Handed Spline Manipulation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '06)*, pages 349–358, Montréal, Québec, Canada. ACM.

[Leganchuk *et al.*, 1998] Leganchuk, A., Zhai, S., and Buxton, W. (1998). Manual and cognitive benefits of two-handed input: an experimental study. *ACM Transactions on Computer-Human Interaction*, 5(4):329–346.

[Lozano *et al.*, 2011] Lozano, C., Jindrich, D., Kahol, K., and Mall, E. T. (2011). The Impact on Musculoskeletal System during Multitouch Tablet Interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*, pages 825–828, Vancouver, BC, Canada. ACM.

[McGookin *et al.*, 2011] McGookin, D., Herteleer, I., and Brewster, S. (2011). Transparency in Mobile Navigation. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems (CHI EA '11)*, pages 1903–1908, Vancouver, BC, Canada. ACM.

[McLachlan *et al.*, 2014] McLachlan, R., Boland, D., and Brewster, S. (2014). Transient and Transitional States: Pressure as an Auxiliary Input Modality for Bimanual Interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*, pages 401–410, Toronto, ON, Canada. ACM Press.

[McLachlan and Brewster, 2015] McLachlan, R. and Brewster, S. (2015). Bimanual Input for Tablet Devices with Pressure and Multi-Touch Gesture. In *Proceedings of the 17th international conference on Human-computer interaction with mobile devices & services (MobileHCI '15)*, Copenhagen, Denmark. ACM.

[McLachlan and Brewster, 2013] McLachlan, R. and Brewster, S. A. (2013). Novel Modalities for Bimanual Scrolling on Tablet Devices. In Kotzé, P., Marsden, G., Lindgaard, G., Wesson, J., and Winckler, M., editors, *Proceedings of IFIP INTERACT 2013*, pages 229–246, Cape Town, South Africa. Springer Berlin Heidelberg.

[Mizobuchi *et al.*, 2005] Mizobuchi, S., Terasaki, S., Keski-Jaskari, T., Nousiainen, J., Ryynanen, M., and Silfverberg, M. (2005). Making an Impression: Force-controlled Pen Input for Handheld Devices. In *CHI '05 Extended Abstracts on Human Factors in Computing Systems (CHI EA '05)*, pages 1661–1664, Portland, OR, USA. ACM.

[Müller *et al.*, 2012] Müller, H., Gove, J., and Webb, J. (2012). Understanding Tablet Use : A Multi-Method Exploration. In *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services (MobileHCI '12)*, pages 1–10, San Francisco, California, USA. ACM.

[Ng *et al.*, 2015] Ng, A., Williamson, J., and Brewster, S. (2015). The Effects of Encumbrance and Mobility on Touch-Based Gesture Interactions for Mobile Phones. In *Proceedings of the 17th international conference on Human-computer interaction with mobile devices & services (MobileHCI '15)*, Copenhagen, Denmark. ACM.

[Ofcom, 2012] Ofcom (2012). Communications Market Report 2012. Technical Report July.

[Ofcom, 2014] Ofcom (2014). Communications Market Report 2014. Technical report.

[Pascoe *et al.*, 2000] Pascoe, J., Ryan, N., and Morse, D. (2000). Using while moving: HCI issues in fieldwork environments. *ACM Transactions on Computer-Human Interaction*, 7(3):417–437.

[Pohl and Murray-smith, 2013] Pohl, H. and Murray-smith, R. (2013). Focused and Casual Interactions : Allowing Users to Vary Their Level of Engagement. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*, pages 2223–2232, Paris, France. ACM.

[Ramos and Balakrishnan, 2005] Ramos, G. and Balakrishnan, R. (2005). Zliding : Fluid Zooming and Sliding for High Precision Parameter Manipulation. In *Proceedings of the 18th Annual ACM Symposium on User Interface Software and Technology (UIST '05)*, pages 143–152, Seattle, WA, USA. ACM.

[Ramos *et al.*, 2004] Ramos, G., Boulos, M., and Balakrishnan, R. (2004). Pressure Widgets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04)*, volume 6, pages 487–494, Vienna, Austria. ACM.

[Schwesig and Poupyrev, 2004] Schwesig, C. and Poupyrev, I. (2004). Gummi: a bendable computer. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '04)*, pages 263–270, Vienna, Austria. ACM.

[Scott *et al.*, 2010] Scott, J., Izadi, S., Rezai, L., and Ruszkowski, D. (2010). RearType: text entry using keys on the back of a device. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '10)*, pages 171–179, Lisbon, Portugal. ACM.

[Sellen *et al.*, 1992] Sellen, A., Kurtenbach, G., and Buxton, W. (1992). The Prevention of Mode Errors Through Sensory Feedback. *Human-Computer Interaction*, 7(2):141–164.

[Shi *et al.*, 2008] Shi, K., Irani, P., Gustafson, S., and Subramanian, S. (2008). PressureFish: a method to improve control of discrete pressure-based input. In *PressureFish: A Method to Improve Control of Discrete Pressure-based Input (CHI '08)*, pages 1295–1298, Florence, Italy. ACM.

[Shi *et al.*, 2009] Shi, K., Subramanian, S., and Irani, P. (2009). PressureMove: Pressure input with mouse movement. In *Human-Computer Interaction IFIP INTERACT 2009*, pages 25–39, Uppsala, Sweden. Springer Berlin Heidelberg.

[Shneiderman and Plaisant, 2005] Shneiderman, B. and Plaisant, C. (2005). *Designing the user interface 4th edition*. Pearson Addison Wesley, USA.

[Spelmezan *et al.*, 2013] Spelmezan, D., Appert, C., Chapuis, O., and Pietriga, E. (2013). Side pressure for bidirectional navigation on small devices. In *Proceedings of the 15th International Conference on Human-computer Interaction with Mobile Devices and Services (MobileHCI '13)*, pages 11–20, Munich, Germany. ACM.

[Srinivasan and Chen, 1993] Srinivasan, M. a. and Chen, J.-s. (1993). Human Performance in Controlling Normal Forces of Contact with Rigid Objects. In *Proc. Advances in Robotics, Mechatronics, and Haptic Interfaces - ASME'93*, volume 49, pages 119–125.

[Stewart *et al.*, 2010] Stewart, C., Rohs, M., Kratz, S., and Essl, G. (2010). Characteristics of pressure-based input for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*, pages 801–810, Atlanta, Georgia, USA. ACM.

[Wagner *et al.*, 2012] Wagner, J., Huot, S., and Mackay, W. (2012). BiTouch and BiPad : Designing Bimanual Interaction for Hand-held Tablets. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*, pages 2317–2326, Austin, Texas, USA. ACM.

[Wigdor *et al.*, 2007] Wigdor, D., Forlines, C., Baudisch, P., Barnwell, J., and Shen, C. (2007). LucidTouch : A See-Through Mobile Device. In *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology (UIST '07)*, pages 269–278, Newport, Rhode Island, USA. ACM.

[Wilson *et al.*, 2011] Wilson, G., Brewster, S., Halvey, M., Crossan, A., and Stewart, C. (2011). The effects of walking, feedback and control method on pressure-based interaction. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '11)*, pages 147–156, Stockholm, Sweden. ACM.

[Wilson *et al.*, 2010] Wilson, G., Stewart, C., and Brewster, S. (2010). Pressure-based menu selection for mobile devices. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '10)*, pages 181–190, Lisbon, Portugal. ACM.

[Wilson, 2013] Wilson, G. A. (2013). *Using Pressure Input and Thermal Feedback to Broaden Haptic Interaction with Mobile Devices*. PhD thesis, University of Glasgow.