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Examining Target Selection Accuracy for Small Interface Items on Tablet Computers

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Abstract

The present investigation aimed to re-examine the issue of touchscreen input accuracy within the context of current generation tablet devices, with a view to exploring the effects of varying target size and varying spacing between multiple targets. In an extension of existing literature, the study aimed specifically to investigate both text-based and graphical targets, and to note the distinction between 'misses' and 'incorrect target hits'. A comprehensive literature review considering research from several domains is presented, together with a snapshot of the current state of the art. A usability testing based experiment with a repeated measures design is then described, the results of which suggest a number of associations as predicted, in addition to several inconclusive findings which are discussed further, along with suggestions for future investigation.

Keywords: Tablet, iPad, Touchscreen Accuracy.

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1. Examining Target Selection Accuracy for Small Interface Items on Tablet Computers

During the past eighteen months, we have borne witness to what potentially equates to a significant paradigm shift in the way we interact with computing devices. To suggest tablet computers have only recently emerged would be factually incorrect, however the current crop of tablets is far removed (in terms of underlying technologies and typical use) from the earlier iterations of the tablet form factor. The current generation, driven largely by the success of Apples *iPad*, is the first to attain mass-market appeal and acceptance, and in doing so presents the user with a novel platform on which to perform tasks, access services and consume media. However, while largely the same data and services are accessed on modern tablets as would have been traditionally using their desk-bound counterparts, tablet computers offer a fundamentally different interaction style in requiring direct manipulation of screen content via touchscreens; a dramatic move away from the status quo of mice and keyboards for everyday computing.

While the apparent simplicity and slickness of touchscreen interaction appears desirable, and does indeed afford the user some such benefits, the adoption of this technology as a system's primary (and indeed, sole) input device is not without its issues. Indeed visiting the existing literature on touchscreens, one notes that there are several usability related concerns which persistently reoccur throughout the development and advancement of touchscreen technology; issues such as accuracy (particularly prevalent when small items on the screen are to be selected) and the occlusion problem (whereby screen content is obscured by the placement of a users finger, an unavoidable consequence of the direct nature of touchscreen input). Such issues, one might suggest, surpass even the relentless pace of technological advancement because they are essentially issues of physicality, issues which algorithms and hardware adaptions alone cannot serve to eliminate entirely. Naturally, that such issues exist is hardly a revelation, and for many years designers of systems and other interested parties have been developing strategies and solutions aimed and minimizing the extent to which such issues impact a user's touchscreen performance. Everyday anecdotal accounts, or indeed hands on experience with any such device however reveal that these issues persist to this day, and impact the performance and quality of experience for users of even the very latest devices.

The intended purpose of the current investigation is to, within the context of current tablets, explore the severity of the principle usability issue which has traditionally arisen from touchscreen interaction: that of accuracy. In order to achieve this, an account of the literature regarding touchscreen and tablet usability will be presented along with a snapshot of the current state of the art in terms of existing touchscreen tablet implementations. A practical assessment will then be detailed which sought to gauge the real-terms accuracy of selecting both textual and graphical targets on a current generation iPad 2 tablet, with findings presented and discussed within the context of touchscreen usability.

1.1 An Overview of the Literature Surrounding Touchscreen Based Devices

At the present time, investigation specifically targeting the current generation of tablet devices is largely notable by its absence from the literature, no doubt as a result of the rapid pace at which these devices have come to market, and the currently still volatile nature of this particular sector of the industry. While touchscreen equipped tablet computers may have only very recently undergone something of a transformation and resurgence however, neither the basic technology nor the concept behind the touchscreen computing device is entirely novel. An established and extensive body of literature surrounding the usability of the touchscreen exists, from which one can learn much regarding the issues and limitations of this type of input device.

It is worth noting therefore that the current review draws on the much broader pool of literature surrounding the touchscreen as an input device, as opposed to research confined solely within the domain of touchscreen tablet computers. Touchscreens have, for many years, been available and deployed on a variety of device types including touchscreen desktop monitors, PDAs and handheld devices, and more recently surface computing systems. While not all of this information is valuable in the specific context of touchscreen tablet computers, to dismiss such previous work would be to overlook many transferable and potentially very useful findings with regards to the touchscreen as an input device.

1.1.1 Traditional or Desk-bound Touchscreen Investigation

If we extend ourselves the opportunity to explore this closely related body of work, one seminal publication with which to start is presented by Sears and Shneiderman (1991), who provide an account of early investigation into the usability of traditional touchscreens. Sears and Schneiderman describe three studies conducted to assess accuracy, performance (in terms of speed) and user preference over a standard touchscreen monitor, a touchscreen monitor with 'stabilisation' applied, and a traditional optical mouse. Numerous related studies are however additionally cited, and some useful conceptual discussion on touchscreen strategies can also be found.

In their opening remarks, Sears and Schneiderman begin by detailing a number of advantages of the touchscreen over alternative input devices, such as the naturally intuitive quality of their operation and subsequent ease of learning, as well as practical advantages such as durability and lack of moving parts. At the same time however, numerous perceived disadvantages are also reported based on findings from other touchscreen investigations conducted around the time, the most prevalent potential weakness being a lack of precision leading to high error rates. This is later attributed largely to "…the problem of returning multiple pixel locations for a single touch". Summarizing several relevant studies, Sears and Schneiderman note how there is a significant amount of variance regarding results, with some studies finding users are capable of single pixel selection accuracy, while others suggest that touchscreen use may result in a significantly high occurrence of errors. Based on the findings of the three studies which they describe and conduct however, Sears and Shneiderman report touchscreens to be a largely accurate and intuitive method of interaction, and advocate their suitability in a number of contexts, suggesting advantages including "…simple operation, ease of learning, rapid performance, and potentially low error rates".

Huang and Lai (2008) more recently also investigated the usability of desktop monitor based touchscreens in a study that sought to establish which factors impact most significantly the usability and user experience of touchscreen interaction. While a number of factors which were presented are perhaps beyond the remit of the current investigation (such as quality of semantics, colour and shape of targets), Huang and Lai noted that the factor determined to be the most significant affecter of touch screen usability was what they referred to as 'touch field', a term which encompassed the size, spacing, location and density of targets. One of the principle findings of this investigation was that from analyses within the factor of touch field, the size of targets was taken by users to be the primary and most influential factor in determining the usability of icons on a touch based interface. The authors briefly discuss that an implication of touchscreen deployment should be increased icon size, as smaller icons are taken to "reduce the usability [of touchscreen interfaces]".

As noted already, the aforementioned investigations involve the use of traditional touchscreens, affixed onto a desktop PC monitor. This represents a significantly different context from that of current tablet devices, in terms of posture and ergonomics, typical usage applications and the technologies used. The fixed and physically stable placement of the touchscreen would also constitute a favourable situation with which to interact with a touchscreen, a luxury that may often not be possible with mobile devices. Consequently, findings observed from these investigations cannot be transferred into the context of current tablet devices, however some important concepts are introduced such as the use of 'stabilization' and discussion regarding touch selection strategies, which are further explored in the following sections.

While the findings of investigation conducted on desk-based touchscreen monitors may not be entirely transferable within the context of tablet devices, the Sears and Schneiderman study in particular suggests that touchscreens certainly show promise, and the study provides grounds for optimism as to the potential usability of touchscreens per se. At the same time, one must also acknowledge however that the uptake of touchscreen technology incorporated into desktop displays is dwarfed by the number of mobile consumer electronic devices which utilize the input method as standard. Consulting the literature surrounding touchscreens in a mobile device context reveals a different set of challenges, and suggests substantial issues of accuracy and occlusion persist.

1.1.2 Touchscreen Investigation Within the Context of Mobile Devices

As noted by Ballard (2007), shifting contexts from desktop to mobile introduces all manner of challenges and variables which may affect the quality and performance of interaction with mobile devices. Factors such as the reduced bandwidth for interaction (in terms of both limited screen size for data output and reduced data entry capability), the unpredictable and potentially distracting nature of the environment, and technical device limitations (such as raw computing power, connectivity etc.) may present significant usability implications. As a result principally of the smaller screen sizes available and subsequent decrease in physical size of the user interface elements that constitute touchscreen targets, mobile touchscreen based devices have almost exclusively relied on the use of a stylus until recent years (a practice which is further discussed later in section 1.4.1). Much of the early mobile investigation into touchscreen usability on mobile devices reflects this.

Ren and Moriya (2000) provide one comprehensive account of stylus based touchscreen performance, in which they discuss touch strategies (which are explored further in section 1.2.1) for stylus driven mobile touchscreens and explore what they refer to as "the smallest maximum size"; the size threshold below which significant differences in performance are observable as size changes, and above which such changes across their selection strategies did not appear significant. Measures of performance in this case were taken to be timings for selection, as well as error rate corresponding to selection accuracy, while single targets were presented ranging in size from one up to nine pixels (in two pixel increments). Ren and Moriya found no significant differences in terms of times across these sizes, but from looking at error data noted that their smallest maximum size for a target was 5 pixels (or a 1.8mm diameter circle) when selected using a stylus with any of the touch strategies presented.

Hourcade and Berkel (2008) also conduced a stylus or pen-based study, however their focus was towards investigating the effects of age on touchscreen performance. Hourcade and Berkel reasoned that evidence suggests age has implications for performance in a number of areas related to touchscreen use such as cognitive, perceptual and motor abilities, and owing to the increasing age of the population this was a useful area to explore. The authors present a complex design which involved the exploration of a number of variables, however particularly worthy of note within the context of the current review were the findings surrounding accuracy in relation to size of onscreen items. Hourcade and Berkel established that target size had a clear and significant bearing on performance, both with regards to accuracy or error rate, and target selection time. Regarding the effects of age, the authors remark upon the relatively encouraging levels of performance achieved by the older subsamples, however do note that particularly in the case of selecting smaller items via tapping, an increase in target size would serve to dramatically improve performance levels, again suggesting issues of accuracy and linking these to target size.

One must at this point acknowledge that the findings presented in these aforementioned studies were obtained in a usage context which again is not entirely representative of the typical use of recent tablet devices. The use of smaller screens, styli for interaction, and consequently stylus driven interfaces (with reduced target sizes) are three factors which render findings from such an investigation again not directly transferable to the domain of current generation tablets. However from such investigation, in spite of the presence of styli (from which one is generally considered to obtain finer, more accurate interaction), a tendency is noted for target size to correlate with touchscreen performance, with targets of a lesser size producing selection accuracy issues.

However very recently, stylus driven PDAs and pocket PC devices have largely given way to the modern smartphone, a change that has carried with it a shift towards direct touchscreen selection by means of a users thumb or fingers, as opposed to a foreign intermediary object such as a stylus. This change in behaviour, largely the result of technological change, has also had implications regarding the touchscreen literature with a number of recent investigations returning to the topic of direct finger or thumb based touchscreen operation.

Lee and Zhai (2009) present one broad investigation which explores several factors affecting the usability of touchscreen soft buttons, comparing these to their hardware equivalents and discussing issues such as tactile and auditory feedback. The authors also however touch on the differences surrounding stylus-based versus direct touchscreen interaction, and further explore implications regarding target size. The authors note that, when a resistive touchscreen equipped Pocket PC was used, there was no significant difference in time taken to select a target between the stylus and direct touch modes of operation, however they observed that direct touch did result in a significantly greater rate of corrective strokes. The authors suggest that this is no surprise, given the “wider and less precise” nature of a bare finger when compared to a stylus. Interestingly and perhaps contrary to what one might expect given recent trends, participants also reported a significant preference for stylus interaction over direct touch. With regards to button size, this was taken to be a significant effector of performance however the authors note that a traditional recommendation they cite from the literature, that soft buttons should be a minimum of 22mm, is not taken to hold since their findings suggest smaller targets can still be selected with a high level of accuracy (and, it is suggested, higher still if a stylus is used).

Parhi, Karlson and Bederson (2006) describe one detailed study investigating the effect of target size on selection accuracy and speed within the context of one handed thumb use on mobile devices. The authors also differentiate between the tasks of selecting one single target versus the selection of multiple targets in quick succession (the latter task is designed to be analogous to text entry on a touchscreen soft keyboard). Parhi et al describe how in the single target tasks, target size (which in this case had five levels varying from 3.8mm up to 11.5mm) had a significant effect on both speed of selection and accuracy. Another variable, location on the screen, was determined to have affected neither time nor accuracy (however subjective user preference did differ between locations). Regarding the serial target results, Parhi et al observed that target size again produced significant differences in time and accuracy, while target location produced no effect (however the interaction between target size and location produced a marked effect on error). Also worth noting is that the significance of effects tended to be greater with regards to the time measurement, as opposed to accuracy (error) measure. The authors conclude by recommending target sizes for single selection tasks should be at least 9.2mm and for serial selection of targets, a minimum size of 9.6mm is suggested.

Park and Han (2010a, 2010b) conducted two related investigations into input accuracy for thumb-based interaction on mobile touchscreen devices, focusing specifically on the effects of target location (25 levels) and target size (3 levels). While also using a Pocket PC type device, in the first case Park and Han (2010a) again found accuracy to have a significant effect on two measures of touchscreen performance; success rate and input offset (the difference between target centre and actual hit). Park and Han (2010a) also determined there to be significant differences in performance between target locations, an effect that seemed to interact with or vary in response to target size. In an additional closely related investigation which featured the same variations of target size and location as well as the same device, Park and Han (2010b) noted that of the three target sizes investigated, the largest at 10mm provided the greatest usability, however a smaller target size of 7mm appeared to offer the best balance between time and accuracy and was thus the recommended target size for any time related applications in a thumb-driven mobile context.

While the context surrounding the studies cited above does indeed appear relatively similar to that of the tablet devices currently under discussion, one notes that the aforementioned investigations assume (based on common smartphone practice) that interaction occurs primarily by use of an individuals thumb. As discussed by the authors, one-handed thumb-based interaction has some significant implications with regards to the motor abilities of users, and potentially renders some locations of the screen more easily accessible than others. While the extent to which location affected performance varied between the findings of Parhi et al (2006) and Park and Han (2010a), one may infer that this issue should be less prevailing on tablet devices given the natural style of interaction with the tablet form factor (the selecting hand is free to move across the screen, and selections are principally made using the index finger).

1.1.3 Investigation Surrounding Surface Computing and Multi-Touch Table-Top Systems

One further avenue of touchscreen investigation which has emerged within the literature in recent years is that surrounding the optical touchscreen technologies deployed on surface computing systems such as the Microsoft Surface. Users tend to interact with the touchscreens on these systems by use of their fingers (frequently index finger), with many such systems also affording users the type of gesture based interaction consistent with current tablets, however not previously offered when using traditional desktop touchscreens. Even on these systems however, which feature much greater display sizes and resolutions, the literature would appear to suggest that issues of accuracy persist.

Forlines et al (2007) describe one early investigation into tabletop input in which direct touch selection is compared with the use of a traditional mouse in terms of user performance and preference. The authors note how a direct touch style of interaction again would appear to afford the user a more “natural” and “compelling” mode of operation, however highlight a tendency in the literature for direct touchscreen input to result in accuracy related errors. Their findings regarding unimanual interaction serve to reinforce this observation, with the mouse outperforming direct touch in terms of selection accuracy and user preference (however direct touch performance was slightly quicker in relation to selection times). In the context of bimanual interaction however, direct touch significantly outperformed indirect selection through two physical input devices across all measures. The authors therefore conclude that designers of tabletop applications specifically requiring individual users to apply unimanual interaction may benefit from considering traditional input methods, despite their indirect nature, due to the more precise levels of accuracy they permit.

Benko, Wilson and Baudisch (2006) also discuss the usability of touchscreen based tabletop systems and an investigation primarily focused at developing multitouch reliant solutions for improving selection and input accuracy. The authors summarise how at the time, the penetration of the touchscreen as a means for data input into general computing devices and applications is still limited owing to “relatively high error rates, arm fatigue, and lack of precision”. The authors cite that this accuracy issue is compounded by the interface design of WIMP (Windows, Icons, Menus and Pointers) interfaces traditionally associated with desktop computing applications, which frequently require high precision input. While the authors might seemingly or implicitly appear to question the suitability of traditional desktop interfaces on touchscreen hardware however, the solutions they later propose centre around adapting user input in order to better accommodate a need for high precision control and accuracy.

Several other investigations also point to a lack of input precision when small user interface items are targeted on touch-based tabletop systems, and indeed propose further solutions aimed at improving selection accuracy (Bartindale et al, 2011; Ahnsallah et al, 2010; Voida et al, 2009). Some of these potential solutions are outlined and discussed in the following section.

1.2 Selection Strategies and Proposed Solutions

Empirical investigation into the usability of touchscreens is not confined to defining and scoping the issue of accuracy, and a number of investigators have attempted to address the issue by proposing and describing numerous potential solutions to enable high precision input. These solutions range from modifications to the low-level technical computation used to interpret the raw data of touch, to significant conceptual shifts in how the interaction is achieved. The purpose of the current section is to briefly outline and discuss some of these proposed mechanisms for addressing the issue of accuracy as described previously.

1.2.1 Selection Strategies

Early discussion of touchscreen usability raised one important consideration; the touch selection strategy used to achieve input. Smartphone technologies and current generation tablets have converged to a point where today there is little variation with regards to this factor, as users have subsequently become accustomed to the dynamic, hybridized strategy currently deployed for selecting items on virtually all current devices. However prior to touchscreens becoming a commonplace input device, Potter et al (1988) described several alterative strategies through which touch selection could occur.

Potter et al propose and explore the use of three separate selection strategies; (i) *Land-On*, the simplest of the strategies where the initial first-impact of the users finger determines the placement or selection, and the cursor lies directly underneath the finger (ii) *First-Contact* where the placement of a users finger is taken to provide “a continuous stream of touch data” and the selection is deemed to be the first selectable target onto which the finger is dragged (where cursor placement again lies directly beneath the finger) and (iii) *Take-Off* whereby the cursor is offset and placed half an inch above the finger, and “selection is made upon release if a target exists at that cursor location”. The authors note that at the time, the former two were encountered in touchscreen use however the third strategy is one which they developed to address the shortcomings of the former methods.

In an experimental comparison of the three strategies, Potter et al observed the *Take-Off* strategy resulted in a statistically significant improvement in accuracy (evidenced by lower error rates) at the expense of a significant increase in time taken. Sears and Schneiderman (1991) later discuss several further investigations of these strategies, the general consensus emerging that *First-Contact* may be the fastest, however results regarding accuracy do not consistently or conclusively favour one strategy over the others. Despite this, Sears and Schniederman opted to feature the *Take-Off* strategy in their 1991 investigation comparing touchscreens with a traditional mouse, and as described previously, found users were able to achieve relatively precise selection accuracy using this method.

1.2.2 Proposed Solutions Featuring Offset Cursors

The *Take-Off* selection strategy as proposed by Potter et al is one of a number of solutions which address the problem of accuracy by offsetting the location of a users touch from the position of the cursor or the point at which interface activation occurs. Benko et al (2006) propose and assess a number of potential solutions for improving accuracy within the context of multitouch tabletop systems, several of which involve the offsetting of a users cursor. *SimPress* was a basic solution which moved the cursor to the very top centre of a 'blob' (the entire surface area of a users touch) with the action of clicking corresponding to a user applying "a small rocking motion with their finger" designed to simulate increased pressure. An experiment conducted in order to assess the effectiveness of the technique determined it was reliable down to a minimum target size of around 8 pixels, and was deemed "a viable option for use for most general selection tasks". *Dual Finger Offset* saw the cursor immediately offset by a fixed, predetermined amount above a users primary finger upon detection of a secondary finger on the screen. An extension of this, *Dual Finger Midpoint* saw the cursor moved to the location which formed the midpoint between a users two fingers on the touchscreen. The authors immediately note however that these techniques do not provide fine control access to all areas of the screen, for example the corners or very edges. The authors proceeded to outline further potential solutions which incorporated the magnification of small portions of the screen and the introduction of virtual sliders and menus, however the implementation of these more abstract solutions renders them unsuitable within the context of tablets, owing to a requirement for both hands to be available.

Bartindale et al (2011) expanded the idea of applying an offset cursor and indirect selection and took the concept even further away from a typical touchscreen interaction style with *SurfaceMouse*, an attempt to emulate the function (and to an extent even the appearance and form) of a traditional mouse on a multitouch surface system. Upon placing their hand on the surface in a posture typical of that when clutching a traditional mouse, users were presented with the *SurfaceMouse*, a graphical render of a mouse on the screen which behaved as a traditional mouse would have, complete with left and right click and even a virtual scroll wheel. The authors acknowledge that the concept of applying a desktop peripheral to the emerging and exciting area of multitouch interaction at first glance may appear "a curious step back" (perhaps even an admission of defeat) however users familiarity with the traditional input peripheral resulted in findings validating the concept and proving its effectiveness. While this solution would indeed solve some of the specific compatibility issues users of legacy software may encounter when working on a tabletop system, within the field of tablets this probably represents little more than a curious reshaping of the problem, as tablet devices offer neither the screen space nor the optical touch sensing technology required to implement *SurfaceMouse*.

One further investigation of note is presented by Vogel and Baudisch (2007) who describe a technique which they refer to as *Shift*, a method which one might construe as an evolution of the offset cursor. The *Shift* solution is primarily targeted at resolving the occlusion problem, and proposes the introduction of a ‘call-out’, which renders (and can magnify) the screen content obscured by the placement of the users finger when required. In their introduction of the technique, Vogel and Baudisch note that traditional offset cursor implementations present three main concerns; (i) they are ultimately slower than direct touch as a result of the user having to adapt and compensate for the offset (ii) as noted by Bartindale et al, offset cursors render certain portions of the screen inaccessible, and (iii) assuming no visual cue is given, ‘walk up and use’ users may not be anticipating the offset and so their first selection is likely to result in a miss (which may have significant implications for kiosk or service systems, for example). Vogel and Baudisch illustrate how by offsetting not only the cursor but also the screen content, and only initiating the mechanism as and when it is required, the aforementioned issues can be resolved. While the authors explicitly state that *Shift* is designed to address the problem of occlusion rather than that of accuracy, their assessment of their implementation of the technique also suggests that, particularly when zooming is incorporated into the call-out, *Shift* additionally becomes well suited to high precision applications and enables highly accurate selection.

It should at this point be noted that further solutions that involve the offsetting of cursors have recently been implemented on a number of devices currently available, and this appears to be a current method of choice for system designers. Some of these real world implementations are further presented in the following section 1.4.4.

1.2.3 Proposed Solutions Featuring Gestures

One alternative avenue for potential solutions which leans on the direct nature of the interaction provided by touchscreens is the use of gestures. The process of ‘drawing’ a gesture using a stylus or ones finger (as opposed to a traditional mouse) is relatively quick and intuitive, and above this it provides a slick and even enjoyable way to interact with on screen content. As such, this practice has been widely adopted by systems designers and manufacturers such as Apple and Google, and features heavily on mobile devices with generic panning gestures and ‘pinch to zoom’ now common on many consumer electronics and computing products. The ability to assign functionality or commands to simple gestures has also been used to assist with precise touchscreen selection techniques by a number of investigators however.

One early example of this is presented by Mizobuchi and Yasumura (2004), who noted how the increasing complexity of interfaces on mobile devices was beginning to necessitate an exploration of additional touchscreen selection methods beyond simply tapping on targets. Mizobuchi and Yasumura proposed a circling solution whereby users would use a stylus or pen to effectively draw a circle around on screen items, and hypothesized that under certain circumstances, this would prove to yield higher levels of performance both regarding accuracy of selections, and time taken to successfully target an item. The procedure used in the investigation saw subjects selecting icons and shapes on one of three grids which varied target size and target spacing, using both tapping and circling techniques. Findings suggested that in the majority of trials and configurations, the tapping selection technique outperformed the proposed circling technique both with regards to error rates and selection times. However, one further finding implied that selection time for the tapping technique varied fairly significantly according the size and shaping configuration of the grid of targets. The authors concluded that although they had to reject several of their experimental hypotheses on the grounds of the traditional tapping technique outperforming the proposed circling technique, there were some specific circumstances under which the circling gesture technique offered advantages, and that further investigation into supplemental, gesture-based selection techniques may still result in more efficient and effective touchscreen interactions.

Yatani et al (2008) propose *Escape*, a gesture based method which transforms or overlays individual targets with a directional indication. Within close proximities, or what Yatana et al refer to as 'Parhi boxes' (after Parhi et al, as outlined previously, suggested touch targets should be no smaller than 9.2mm squared), each target is assigned a different direction and a different colour. In order to select a target and differentiate it from its immediate neighbours, the user simply has to place a finger or thumb within the region that the target is located, and then make a swiping gesture in the direction that their desired target points towards. Using this technique, Yatani et al claim users are able to select very small targets, located within very close proximities (or indeed overlapping) other targets; and because the selection process requires the user to move their finger across the screen, the occlusion problem is also to an extent resolved. Yatani et al compare *Escape* with Vogel and Baudisch's *Shift* (as described above) and determine that their own technique compares favourably regarding time while producing no significant increase in error rate. In the case of *Escape*, accuracy was also less affected by the size of targets which were presented. Yatani et al note however that their findings are based on their own reimplementation of *Shift*, and comparing their findings with those originally published by Vogel and Baudisch, *Shift* does appear to perform slightly better with regards to larger targets (above 18 pixels). The authors also acknowledge a number of weaknesses to *Escape*; for example, in applications where the activation of background space performs a function (e.g. 'drag to pan' across a map), their technique reduces significantly and without visual indication the 'open space' available to the user. Escape also does not fair so well with targets close to the edge of the screen (assuming gestures are only supported on the screen and not the bezel), and owing to the direction indication which must be assigned to each target, a decreased potential maximum number of on screen targets is available. Yang et al (2011) also point out that due to *Escape* requiring targets to be transformed, while it may be applied to new applications with relative ease it would not be available on legacy software without such applications going through this transformation.

Karlson, Bederson and SanGiovanni (2005) discuss two potential gesture-based solutions which further explore the concept of transforming the user interface, *AppLens* and *LaunchTile*. Both solutions rely on selective zooming and re-rendering of information in response to gesture based commands, and are proposed as a means of enhancing the interface of contemporary PDAs and smartphones to accommodate comfortable one-handed operation in a move away from the stylus and hardware key based navigation of the time. Both are also roughly analogous to ‘homescreen replacements’ or ‘shell’ applications, which act as a portal through which to access the existing applications on the device. *AppLens* presents a grid of nine ‘dynamic tiles’ (as opposed to launch icons), with each containing an overview of information for the application it represents. Tiles can be expanded to a ‘context’ state which increases the visible size of the tile, decreasing other tiles and applying a level of transparency, or into a ‘full’ state which constitutes the default presentation of the maximized application. Tiles are selected via a series of directional gestures to the lower portion of the screen, with visual feedback provided by a ‘cursor’ which comprises a coloured rectangle around the selected tile. *LaunchTile* utilizes a similar method, however explores fitting even more tiles on the homescreen, which are divided into ‘zones’ (each zone appearing similar to the *AppLens* homescreen) and selected using panning gestures applied to the touchscreen, or interaction with a soft joystick implementation which the authors refer to as ‘blue’. The authors conduct usability testing to assess the prototypes of each solution, with findings suggesting “generally positive reactions” to the interface arrangements and “modest yet positively skewed satisfaction ratings for gesture interaction as well as what we consider very reasonably performance”. It should be noted however that the scope of this solution is limited, and while the proposed techniques may assist users with launching applications using a single thumb (in improving the accessibility of certain areas of the screen), the solution is not applicable to many of the activities which users of todays technology may undertake (activities such as web browsing or in-app navigation for example) and may not transfer well to the larger form factor of tablet devices.

Karlson and Bederson (2007) later proposed one further technique, also aimed at addressing one-handed, thumb-based navigation, which they term *ThumbSpace*. The technique in essence constitutes converting a user-defined portion of the screen into a touch surface, which, with the addition of a dynamic cursor for visual feedback, behaves in a way somewhat akin to modern laptop trackpad. The *ThumbSpace* region however actually constitutes an miniature proxy of the larger display space, so for example to select a target located toward the top right of the display, the user would place their thumb toward the top right of the *ThumbSpace*, and make directional dragging gestures (using the cursor for visual reference) until the desired item is selected. The user would then complete the selection by lifting their thumb from the screen, as per the *Take-Off* strategy. In a user-testing based assessment of a *ThumbSpace* prototype, the authors find promise in the proposed solution; while slower than direct selection, their technique provided greater accuracy and higher levels of user satisfaction. The authors however concede that such a solution is unlikely to provide an immediate replacement to direct interaction, due to something of a steeper learning (or performance improvement) curve than anticipated, owing to the mental demand of mastering the technique.

1.2.4 Proposed Solutions Featuring Fine-Tuning of Direct Selection

One further approach that has been identified within the literature concerns the study of low level, detailed analysis of the precise biomechanics of touch, with an ultimate aim of identifying and exploring the causes of the discrepancies which occur between a users intended and actual touch locations. This bottom up, data-driven approach hints at a solution based on fine-tuning, accommodating and compensating for the quirks of human interaction as opposed to conceptually shifting or reshaping the interaction.

Holz and Baudisch (2011) present a re-examination of touch interaction that delves into gross detail, exploring the mental models users possess and examining how these mental models and indeed touchscreen performance are affected by precise finger postures (measured in terms of roll, pitch and yaw). The authors note how traditionally, one of the core assumptions of touchscreen interaction amongst systems designers and users alike is that the contact area, specifically the centre of the contact area, encodes the precise location which the user seeks to target. Holz and Baudisch however challenge this assumption based on previous and current findings, and reason that the "contact area model" of interpretation is not sufficiently flexible to account for different finger postures, which subsequently means it is often not compatible with the users mental model. Through close scrutiny of users actual finger placements, as well as their perceived targeting strategies and comprehension of the interaction (which the authors require their subjects to verbally articulate), the authors present a "*projected centre model*", which they claim reduces error offsets over the traditional model. The new model recognizes that in terms of visual reference, users are implicitly forced to base their targeting on the above fingernail, as opposed to the pad of the finger which comes into contact with the surface (due to obvious occlusion). This results in a parallax between the visible surface of the finger and the contact area, which manifests itself in errors of various offsets and directions according to the posture of the finger. Through the new model, the authors claim that the strategies used by individuals to acquire and precisely select specific targets on touchscreens could be better accommodated, with the ultimate result being a reduction of error.

In two related investigations, Kwon et al (2009) and Kwon et al (2010) also recognize and closely examine the distinctions between the users actual touch point, the wider contact or activation area resultant from the touch, and the effect this has on closely spaced targets. The 2009 study focuses investigation specifically within the context of text entry on virtual soft keyboards, while the 2010 study expands in scope to consider graphical targets such as icons. In the 2009 study, Kwon et al propose a regional error correction technique to improve accuracy in touchscreen typing, which takes the form of a system similar to Nuance's XT9 (Nuance, 2011). The solution therefore does not seek to address the accuracy problem directly, however constitutes something of a 'coping strategy' to determine the likelihood of activation for each key based on contact area spread and on context (i.e. determining from a lexicon based on the preceding and following key presses). Naturally, in discrete selection activities such as navigating the internet for example, such meaningful context is not available, rendering the applications of such a solution limited to within the given field of text entry. In the 2010 study however, Kwon et al propose *Two-Mode Target Selection*, a method which differentiates between what the authors refer to as ambiguous and unambiguous selections. The technique centres around the concept of an activation area, however the activation area which the authors suggest does not constitute the actual 'blob' size and shape of the physical contact area (as described by Holz and Baudisch above), however to an extent emulates this by providing a circular threshold surrounding the specific sensed location of the touch. In effect, this activation area comprises of the section of the screen which a user's finger would likely obscure during interaction (as was necessary to be determined for the *Shift* method described previously) with the authors suppose to be around 20 pixels or 3.54mm. If only a single target is present within the activation area, unambiguous mode (UM) is initiated and the interaction may proceed as a standard direct touch interaction (the authors propose this uses the 'bubble cursor' which activates the one single target within the activation area even if the users touch was actually located on any inactive space immediately surrounding the target). However, if multiple potential targets are present within the activation area, ambiguous mode (IM) is initiated. The authors reason that when a screen press has been registered as being in ambiguous mode, there is insufficient information to determine which target should be activated, and so further interaction is required by the user. Kwon et al (2010) do not formulate their own actual solution to this, however propose the TapTap method by Roudate et al (2008), as described below.

1.2.5 Other Techniques Proposed

Roudate et al (2008) present two further techniques which are again designed to assist with thumb-based navigation on mobile devices, alleviating three major limitations of existing techniques which they identify from the literature (and which are discussed previously); accuracy, occlusion and reach or target location. *TapTap* is a simple proposition, which comprises a modification to the standard direct touch paradigm while *MagStick* is essentially a modified offset cursor that relies on dragging. When using *TapTap*, a user directly aims for a target as in a standard interaction, however upon selecting the target or the space immediately surrounding the target, a large magnified representation of the screen area on they tapped on is overlaid over on the centre of the screen, upon which the user again taps to complete their selection. The magnification assures that even if the original target is small and not successfully hit, the 'second chance' which the technique affords the user provides a larger and thus easier to hit target. *MagStick* provides the user with an offset cursor comprising a two-piece stick or wand, which pivots around the point at which the users thumb made contact with the screen. The user would, for example, tap in the centre of the screen for a target above centre, drag the stick down (resulting in the stick extending symmetrically above the pivot point) and the *MagStick* would then be drawn to possible targets by directional dragging, aided through a virtualized 'magnetic' effect, attracting the cursor to the 'magnetic' targets and thus simplifying the process of honing in on targets. In their assessment of the two techniques, Roudate et al find these techniques produce a significantly lower error rate when compared to standard direct touch, and also find their techniques to produce fewer errors when compared to some of the other proposed solutions such as *Shift* and *ThumbSpace* and an offset cursor (as outlined previously). The authors also find their prototype solutions to be faster than all competing strategies tested, with the exception of direct touch, however argue that due to the number of errors which result from direct touch and comparative accuracy of *TapTap*, they suggest their technique would be faster under actual use. One does note however that unless combined with a mechanism such as Kwon et al's *Two Mode Target Selection,* the most significantly implication of *TapTap* is that every interaction would require twice as many screen taps, which perhaps renders the solution somewhat inelegant, notwithstanding its simplicity and effectiveness.

A number of further solutions have also been proposed which may have implications for improving the accuracy or reducing the on-screen occlusion which results from touch based interaction. Several investigations have considered the advantages that may be offered by augmenting one touch screen device with additional hardware devices to assist in locating and selecting content, for example using a smartphone as a virtual 'lens' for interacting with a surface or table-top system (Voida, 2009; Ruan et al). Some additional work has explored the idea of moving the interaction to the rear of a portable device, for example providing users with a touchpad or touch sensitive area on the back of a mobile device (Wobrock et al, 2008; Scot et al, 2010), which both solves and introduces further issues of occlusion and accuracy. Such solutions introduce a hardware requirement which may be undesirable, as the extent to which these ideas are feasible on current devices can be can be called in question. This is by no means to criticize the proposal of radical new interaction paradigms, however such ideas fall beyond the scope of the current investigation.

1.3 Related Models and Theories

In addition to work focusing directly on the usability of touchscreens, one might also find value in broadening the scope of the current investigation to take account of further relevant literature from beyond the domain of usability or even human computer interaction. One example of highly relevant work undertaken in a different context is the often cited Fitts' (1954) law concerning the factors influencing rapid aimed movement toward a target.

Although Fitts' law has been represented a number of different ways, the model fundamentally describes how the time taken to 'point' to and acquire any given target is determined as a function primarily of two main factors; the width (size) of the target, and the distance to target from the starting location. The model therefore dictates that targets which are either very small, or else located far from the starting point will be more time consuming to acquire. The model is further taken to describe the trade-off, in terms of speed versus accuracy, which occurs when an item is targeted. As a result, the model is frequently used in the analysis or comparison of different interactions, and is also very useful in prediction exercises, for example where one may be attempting to determine efficiency for novel input devices or similar (Soukoreff & MacKenzie, 2004).

While Fitts' law is generally taken to be robust when applied to traditional pointing devices such as mice or joysticks in controlling onscreen cursors (Soukoreff and MacKenzie), the extent to which Fitts' law is applicable within the context of touchscreen interaction is debatable. Sears and Schneiderman (1992) outline several concerns which challenge the extent to which the law (in the form used for traditional input devices) is applicable to touch interaction, noting an observation that touchscreen use is inherently different in a few ways, for example there is no time required to locate the hardware device used to control the cursor, and indeed in many touchscreen applications the cursor is not present on the screen until the touch of a users finger has already been registered, at which point the cursor is placed near the finger. This represents a significantly different opening to the interaction, on the basis there is no fixed determinable starting location. The authors consequently propose an adaptation of Fitts' model which accounts for each of these factors, where the time is measured to initially place a finger on the screen, and then further the time is also measured for the movement of the cursor to that location.

Additionally, some implications of the law which have been widely demonstrated within the context of traditional pointing devices do not extend to touch based interaction. For example, one commonly cited interface design suggestion derived from Fitts' model is that targets located along the edges or corners of the screen, while located further from the screen centre, are easily accessible even if they actually comprise of only thin borders or contain only a small surface area. This is because using traditional cursor based interaction, one can not 'overshoot' a target at the screen edge, even if they continue to move the pointing device in that given direction. This effectively results in such targets having a hypothetical infinite width in one dimension, and based on the importance of the width factor within the model, such targets are generally very quick to acquire. However, in a touch based interaction, targets located at screen edges to not contain infinite width because the borders of the screen no longer form constraints past which it is impossible to move. Some authors point to further areas relevant to touch based interaction within which Fitts' law is not applicable, such as time prediction within gesture based interaction (Costagliola et al, 2011) and in some cases, dragging operations (Forlines et al, 2007). Ren and Moriya (2000), in a suggestion for furture study, also remark upon how Fitts' law has not been studied within the context of alternative selection strategies.

Numerous other studies, including some of those presented above, have however discussed or successfully applied Fitts' law within the area of touch. In a study which not only features touch interaction, but in fact complex data entry while subjects are in motion, Lin et al (2007) present findings that are highly in line with Fitts' law, commenting that the model is robust enough to be applied even in the context of challenging every day use (simulated by an obstacle course). The results of the investigation by Parhi et al (2006) largely confirm to Fitts' law, however the authors do note one finding which contradicts the model. Yang et al (2011) also perform a Fitts' law analysis on their data, concluding that their findings "high conformed to Fitts' Law".

In addition to Fitts' law, others within the literature surrounding touchscreen based interaction have also raised further models including *Steering Law*, an adaptation of Fitts' law which accounts for time taken to steer through a two dimensional path (Accot and Zhai, 1997) and *Hick-Hyman Law*, an information-theoretic law focusing on selection based on complexity of choice. The discussion of these principles however extends beyond the scope of the current review.

1.4 The Current State of the Art

In addition to the literature as described above, an account of current trends, technologies and solutions is given in this section to provide additional context to the current investigation, offer some technical grounding as to the capabilities and characteristics of some relevant technologies, and to juxtapose the efforts of academia and industry in addressing the accuracy related concerns surrounding touchscreen usability.

1.4.1 Implications of Different Touchscreen Technologies

In order to fully understand the issues which surround touchscreens, one also must possess at least a basic knowledge as to the types of touchscreen available, the technologies upon which they are based, and the implications with regards to usability issues and performance offered. One significant implication of the underlying technology of the touchscreen for example is the case of the stylus.

During the early years of touchscreen operation and primarily within the context of mobile devices such as PDAs and Pocket PCs, the use of styli was commonplace and was perhaps the preferred method for addressing the accuracy related shortcomings of touchscreen technology of the time. Styli extended the user several other advantages above increasing accuracy (e.g. due to thin shafts and fine points styli minimize occlusion, they also conformed to users' familiarity with pen and paper in improving the experience of writing on screen which was a common text entry method, they enable users to sketch or annotate more naturally; and furthermore they enabled gloved users to accurately select items), however the tapered point of a stylus primarily served to increase accuracy when selecting the often very small items on the screens of mobile devices. The use of these styli (or indeed any other object which tapered to a point) to select on screen items was possible because the touchscreens implemented on such devices were resistive, and were mechanically activated based on pressure.

The majority of current tablet devices however rely on a different underlying technology to detect touch. Within the past 5 years or so in the context of consumer electronics and mobile devices, the previously dominant resistive touchscreen has been largely replaced by the use of capacitive touchscreens, which detect touch by sensing changes of capacitance generated by the electroconductive nature of a users finger on the touchscreen surface. While both techniques are capable of high precision sensing, capacitive screens require less pressure to sense activation, and they also allow the tracking of multiple touches, which enables recent capacitive devices to take advantage of multitouch gestures. The appeal and slickness of these multitouch gestures combined with the simplicity with which items can be directly selected onscreen without resorting to the use of a stylus are factors which have driven the uptake of this technology, and it is very much the technology of choice amongst current and near-future generations of tablet devices.

While resistive and capacitive touchscreens are prevalent on recent and current mobile touchscreen consumer technology, one should note the presence of several other techniques for sensing touch. One such further technique which has attracted significant attention in recent years is that of optical, camera based methods, such as those deployed on the *Microsoft Surface*, *Reactable* and many other surface based computing systems. Such systems use imaging technology to capture the absolute raw data of user touches, which are referred to as 'blobs', and interpreted at a software level on the computer. Numerous other technologies have also been developed, such as infrared touchscreens which were adopted on early monitors, active or electromagnetic inductive digitizers which accept powered stylus pen (but not finger touch) input and even touchscreens using acoustic or ultrasonic signals.

This variety in the underlying technologies used and the subsequent array of different types of touchscreen available presents challenges to researchers in the field, both regarding the prevalence and assessment of usability considerations for touchscreens, and the resulting conceptual solutions which can be proposed. Where a stylus is used on a resistive screen for example, the occurrence of the occlusion problem is to an extent minimized as the contact area is obscured only by the relatively thin shaft of a stylus, compared to the entirety of a users finger(s) or hand on a capacitive touchscreen. Likewise where, for example, a potential conceptual solution is proposed to improve selection accuracy by utilising a multi fingered gesture, technical constraints render such a solution unfeasible for a resistive touchscreen. It should be noted then, that one caveat with investigation into touchscreen usability dictates that highly specific findings and proposed solutions can rarely if ever be of a 'one size fits all' nature. Consequently, though for the purposes of the current literature review the touchscreen is considered as a homogenous whole, as one class of input device; any highly specific findings presented in the area are potentially applicable only within the context and domain of the specific technology in which they were investigated.

1.4.2 Display Resolution

One area that has also witnessed significant development year on year is that of display resolution. Early investigation into touchscreens attempted to gauge at a pixel level the performance in terms of accuracy which a user could achieve during touch screen interaction. However there is a fundamental flaw with the idea of using a pixel as a form of measurement; it does not remain at a fixed or constant size, it is device dependent. This effectively means that the validity of any claims of the nature 'users can select a target of x pixels in size' is confined solely within the realm of the specific setup used in that investigation.

With the introduction of high definition display technology and content, and more recently the introduction of Apples iPhone 4 in 2010, consumers and the media have a renewed interest in the 'sharpness' of displays. Within the context of smartphone-centric publications and magazines, pixel density is becoming a frequently cited metric used in the comparison of different handsets. The retina display present on the iPhone 4 for example has a pixel density of 326 pixels per inch, at which it has been claimed individual pixels are no longer discernable to the naked eye. This of course renders obsolete the notion, as has previously been claimed, that users are able to successfully target single pixels using a touchscreen; if pixels are now becoming too small to see, they evidently cannot be reliably and accurately targeted.

This again has significant implications with regards to the stabilization and noise reduction deployed in touch sensing systems, as activation areas cover an increasing number of pixels with displays providing ever increasing pixel density. As expressed previously then, investigations which provide indications of target or spacing sizes in terms of pixels must be considered to be strictly only representative within their given contexts in terms of the hardware used. Where sizes are expressed in standard units of spatial measurement however, i.e. millimetres, results are likely more transferable across a range of devices, screen sizes and resolutions.

1.4.3 Industry Guidelines for Developers

As indicated in the literature review above, a number of investigations have produced findings from which a variety of guidelines have been derived, for example with regards to the minimum sizes at which targets should be presented to users of touchscreen interfaces. There are however further guidelines provided to applications developers for mobile technologies, which are often provided by hardware vendors or systems designers, from which one can obtain a picture of common practice surrounding touchscreen user interface design.

In the iOS developer documentation, Apple recommend developers assign target areas of "about 44 x 44 points" (Apple, 2011) and also suggest that targets should not be spaced too closely, however they do not define or suggest any further information regarding spacing or size. Apple note that by not following the above guidance and using interface elements that require users to aim more carefully or indeed miss, an application may become "…much less enjoyable, or even impossible, to use".

Nokia provide somewhat more detailed guidance, suggesting that targets should be "7 x 7 mm with 1 mm gaps for index finger usage" or "8 x 8 mm with 2 mm gaps for thumb usage" (Nokia, 2009). Nokia also suggest list items should be spaced with at least 5 mm line spacing, and provide some further information suggesting "…the user is more likely to touch higher on the button by mistake than either side". Nokia additionally suggest that for touchscreen interactions, selectable content should not be placed to closely to the borders of the screen, and that "The visible area of the component and the component's active area should be identical", although also stipulate a few acceptable exceptions (such as scrollbars, which should have a wider active area than visible area).

Microsoft (2011)(at the time of writing, in reference to Windows Phone 7) present a comprehensive guide for developers to ensure their applications are touch friendly, in which it states "Extensive user testing has dictated that 9 mm square be the ideal touch target size across all Microsoft touch platforms". Microsoft however differentiates between the 'ideal' target size of 9mm, and a small minimum size of 7mm where warranted, with a caveat that developers should only resort to a 7mm target height where target width would be much larger- at least 15mm. In contrast to Nokia's guidance, the Microsoft document suggests that the touch target can be larger than the 'visual asset', and while it doesn't recommend this, Microsoft do suggest that visual asset sizes down to a minimum of 4.5mm are acceptable. The Microsoft guidelines also emphasize the importance of visual spacing or padding between items, suggesting a very minimum of 2mm even between visual assets as small as checkboxes. Interestingly, the guidelines also state:

> "Some controls, such as the on-screen keyboard and the hyperlink controls, use algorithms to improve touch accuracy.
>
> Exceptions like keyboard and hyperlink lists need to have correction mechanisms like hit target resizing algorithms or zoom to enable better hit targets. In most cases, the height of the target is more importance that the width…"

Unfortunately no further information is given regarding these corrective algorithms, possibly as such information would be of limited use to the developers to whom the document is addressed.

It should be noted that the Nokia and Microsoft guidelines given above are explicitly provided in the context of smartphone devices, which naturally feature smaller screens and increasingly, higher pixel densities than current tablet devices. However, as these target sizes are expressed in terms of physical sizes and correspond to use on devices with similar or often identical screen technology, it is likely that these guidelines are applicable and indeed used to help shape the interfaces of tablet based applications.

1.4.4 Solutions Currently Available

As stated, issues of accuracy and occlusion are well documented in the literature and commonly encountered with hands-on usage of touchscreen devices. A number of solutions are incorporated into current devices which do however provide some respite for users, enabling precision selection through several interface mechanisms, some of which closely resemble the solutions proposed in academia. The current section describes some of the implementations which appear on several portable computing and Smartphone systems to assist users with fine selection or reduce occlusion.

The Apple iPad (which forms the target device upon which the current investigation is based) features one immediate solution for precise selection, specifically in the context of text selection or editing, during which the user may wish to make very fine selections such as placing the text cursor between the letters of a word (to insert a letter, for example). Context permitting, upon tapping and holding on the screen, users of the iPad are presented with a virtual magnifying glass (see figure 1) which in fact closely resembles the *Shift* solution described previously. The magnifying glass presents the portion of the screen currently directly under the finger in a callout, which is placed above the users finger, thus removing the occlusion effect preventing one from seeing screen content immediately underneath the finger. Additionally, this implementation places a cursor within the callout, and also magnifies the callout which enables high precision selection to be achieved.

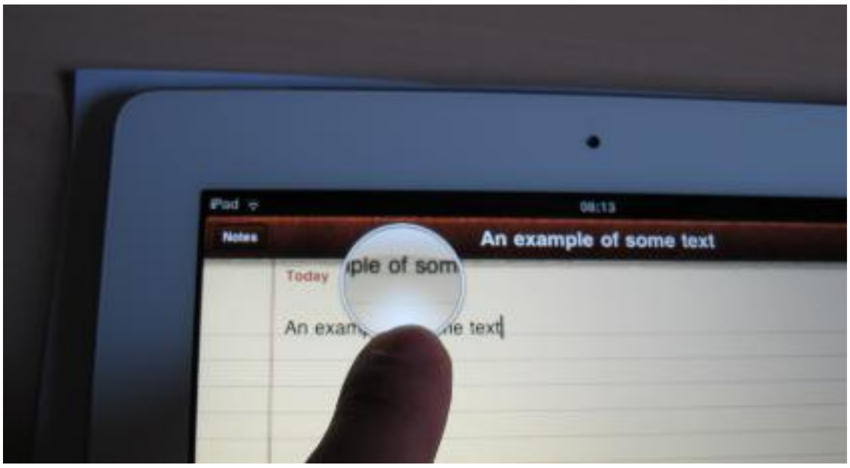

Figure 1: The 'Magnifying Glass' on the iPad

Devices using the Windows Phone 7 operating system are also provided with a mechanism to aid cursor placement during text editing, however this solution takes the form of an offset text cursor (see figure 2) which 'snaps' between letters and words. While the cursor is not freely moveable (in the sense that a traditional mouse cursor is able to move in any dimension to target any available area of the screen) its precise placement is determined through an offset dragging gesture, which again enables precise locating and helps to reduce the effects of occlusion.

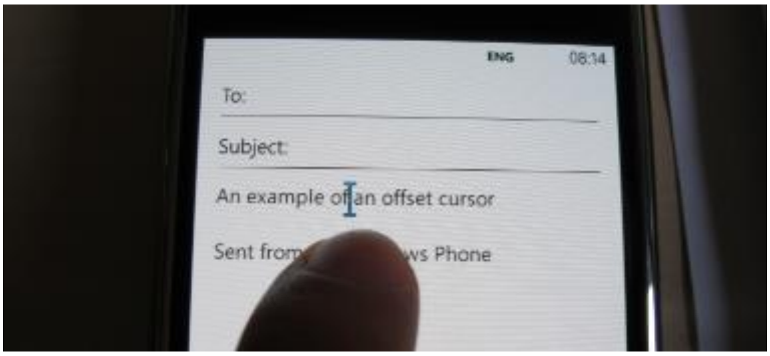

Figure 2: The Offset Cursor on a Windows Phone Handset

Another common mechanism used in aiding targeting on touchscreen devices is the use of virtual 'handles', which are commonly used to make or amend text selections, for example highlighting text to be copied. These 'handles' (see figure 3) are implemented on several devices, and help to emulate the 'click and drag' interaction of a traditional mouse, but also serve to increase the accuracy with which can make or amend a selection by providing the user with an element to 'drag' into position.

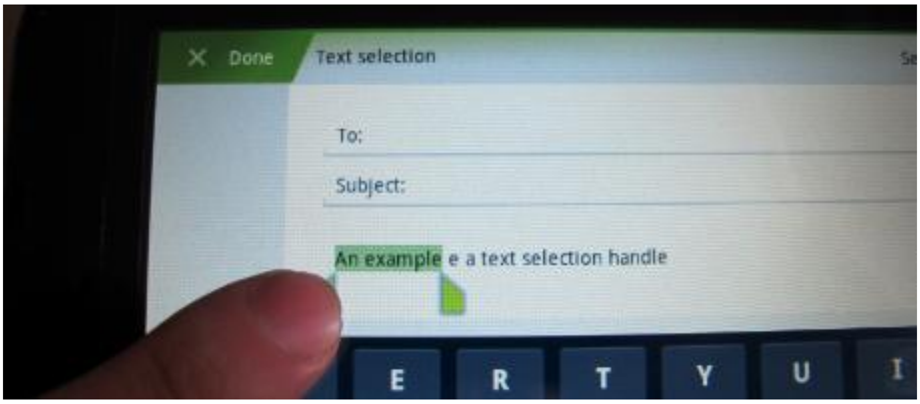

Figure 3: 'Handles' for Text Manipulation

In a few limited contexts, the latest version of Google's Android operating system Honeycomb (developed principally for use on tablet devices) also applies a mechanism similar to the offset cursor, however providing visual feedback by visually highlighting the item currently under selection as opposed to providing a cursor (see figure 4). The method is very similar to the 'take off' selection strategy as discussed earlier, however provides an increased offset distance and different visual cue to that originally proposed in the take-off selection strategy.

Figure 4: An Implementation of the 'Take-Off' Strategy (with extended visual offset)

It should be noted that the majority of these devices also incorporate some form of 'behind the scenes' stabilization, the precise mechanics of which are not so easily discernable. Commonly however, the selectable region of a touch target is expanded beyond the visual surface area of the target to accommodate for selections made to the very edges of, or in actual fact narrowly missing the target. The effectiveness of these corrective measures and the degree to which they accommodate erroneous input varies from implementation to implementation, and is often also determined to an extent by context (i.e. the density of targets). The dynamic adjustment of selection screen areas based on activation location is another potential solution that one notes is previously discussed in the literature.

One further feature worthy of note within the current context and implemented in the majority of current mobile operating systems is the 'pinch to zoom' function. While this function may not be tasked exclusively with addressing input accuracy or occlusion, one notes that this recently introduced gesture which has quickly become a generic standard, provides the user with a quick, one handed and nonintrusive way of effectively increasing target size which was not available (or not so seamlessly implemented) on older Smartphone, PDA and tablet PC touchscreen devices. The ease and control with which this zooming can be initiated has resulted in what has quickly become a common adaptive strategy for many users looking to select small targets. One should also recognize however that such a technique does not constitute a genuine 'solution' to the problem as it does not increase the actual precision of the interaction, rather it introduces an additional interaction step than can be used to re-render screen content in a more touch accessible manner in the absence of a method to reliably target small items at their actual size.

1.4.5 Tablets, past and present

In order to clarify the scope of the present investigation, a brief word regarding the recent history of the form factor of tablet devices may also be of value, particularly as these devices have evolved rapidly within the past decade.

Until relatively recently, the term 'tablet' within a computing context would largely have been taken to refer to a 'tablet PC'. Traditionally, tablet PCs have often been modified laptop or notebook computers, featuring (most frequently, though no exclusively) an active digitizer and accepting pen based input. The physical form factor of the majority of these devices has traditionally been convertible, or *netvertible* (see figure 5), with many tablet devices essentially comprising of a laptop with a rotating screen and powered stylus for input. One important point regarding these traditional tablet PCs is that although they afforded the user a direct means with which to manipulate screen content, the touchscreen functionality and stylus of these devices was often a supplemental input method tasked primarily with enabling sketching, handwriting and jotting down annotations onto documents, while general navigation was often reserved for traditional input methods. Even in the case of tablet PCs which did not assume a convertible form factor, the touchscreen was often augmented with additional hardware controls such as joysticks and jog-dials, to provide alternative means for navigating the device. Such devices also differed from the current generation of tablet computers in a number of other areas; such as the software used and subsequent graphical interfaces presented (with tablet PCs relying on desktop operating systems with some touch-aware adaptions, such as Windows XP Tablet Edition), in terms of typical usage applications (with tablet PCs most frequently reserved for specialized applications) and availability (owing to their niche product status and often prohibitive cost).

Around 2005, Nokia introduced a product named the Nokia Internet Tablet, which comprised somewhat of a hybrid between high end PDA's of the time, and low-end UMPCs (ultra mobile PCs; devices which provided full blown PC software and hardware in very small form factors with screen sizes around 5"+). The Nokia Internet Tablet was envisioned primarily as a consumer-facing media consumption appliance, and was supposed to offer the user a rich online experience comparable to browsing on a laptop or notebook for example. With a screen size of around 4.1 inches and again a prohibitively high price however, the device failed to make a large impact on the market and remained something of a niche product (although several further iterations of the Nokia Internet Tablet line were developed and marketed in the following years). The device did however generate some interest and could be said to have played a role in introducing a new class or form factor of device, the MID or Mobile Internet Device. Further attempts at producing these Internet tablets or MIDs were made by a number of smaller manufacturers (e.q. SmartQ, Gigabye, Aigo), however again such devices failed to make any significant impact on the market, and were not sold in large numbers.

In something of a digression from the tablet form factor but still worthy of note in this context, in 2007 the Netbook emerged. While these devices had a more traditional 'clamshell' laptop or notebook form factor, they essentially constituted portable, relatively cheap appliances mainly used for Internet browsing and media consumption (critics of the concept rightly pointed out that the limited sizes of netbook screens and keyboards did not lend themselves well to productivity purposes). The original Asus EeePC that introduced the netbook concept sold in high volumes and was generally well received however, a reaction that can be extended to the netbook concept in general. Although these are fundamentally different devices to current tablets, the unquestionable success of the netbook concept served to validate the idea of relatively inexpensive, highly mobile 'second computers' primarily for browsing and media consumption. In proving the viability of this concept, the netbook forms an important part of the context in which the current generation of tablet computers has emerged.

In 2010, Apple unveiled and released the iPad, which is widely credited for beginning what has often been dubbed the 'tablet revolution' in the media. While one can draw parallels between previous devices and the iPad, the iPad could be said to redefine the tablet form factor in a way which previous devices did not manage to achieve. In basing the tablet on an ARM-based hardware architecture and using their mobile operating system iOS (as opposed to the Mac OS used on their laptop and desktop computers), Apple differentiate the product clearly from a traditional computer in a way which the majority of tablet-style devices which came before it did not.

The marketplace for tablet devices has quickly become both crowded and diverse however and as of the current time, there are dozens of competing devices offered by a large number of manufacturers, which vary in terms of operating system (Google's Android being the most prevalent next to iOS), size, underlying technologies and form factor (with sliding, docking and folding tablets coming to market). The Apple iPad however still constitutes something of a prototypical tablet, owing to its huge success in terms of market share and a form factor and screen size which is broadly representative of the vast majority of current tablet devices.

One final point worthy of note; in 2012 Microsoft will release Windows 8, the next major mass-market iteration of what has until now been an operating system largely confined to traditional computing devices. Windows 8 however presents a radical departure from the traditional Windows graphical interface, and adopts the 'Metro' UI (an interface carried from its mobile operating system Windows Phone 7) as a major component of its shell. Microsoft has also announced that the operating system will for the first time run on the ARM architecture which accounts almost exclusively for the processing technology incorporated into Smartphones as well as the majority of current tablets including the iPad. This move, in contrast to Apple's philosophy, merges the distinction between the traditional PC and the new class of tablets. The ultimate implications of these factors are of course not currently understood and as such, the tablet device represents something of a moving target; it is currently still transforming and undergoing significant change in a number of areas, hence the inclusion of this section in the current investigation.

1.5 Aims and Rationale for the Current Investigation

Returning to the current investigation, as observed, a significant body of evidence suggests that touchscreens inherently suffer from accuracy related issues, which affect users performance and quality of experience. Despite this, the tablet device form factor, which relies heavily on touchscreen technology as means of its primary input method, is becoming increasingly prevalent. The pace at which these devices have developed and seen mass-market acceptance has resulted in a lack of accessible, empirical investigation addressing their usability. Various reasoning has been presented as to why the closely related research which has centred on similar domains (smartphones, touchscreen desktop computers and surface computing), while useful, may not be directly transferable to this new class of devices.

From reviewing the literature, one notes that where investigation into the usability of touchscreens has been conducted, almost all of this investigation has focused on timings or percentages of correct hits as a measure of user performance. A number of these investigations have also involved the targeting of isolated, individual targets of various sizes (although some exceptions are noted). While this has provided some useful insight into what constitutes a target that users *can* acquire, one question that remains largely unchallenged in the literature surrounds performance regarding mishits or incorrect target hits.

While this concept may initially appear somewhat obtuse, there is potentially an important distinction to be noted between missing a target by hitting the 'background' or plain space, and missing a target by instead striking an alternative target. If we consider an example context of usage such as web browsing, missing a hyperlink on a webpage and instead hitting the space surrounding the link is of relatively little consequence, the user simply reattempts to hit the desired target. However in the same scenario, missing a link by activating an incorrect adjacent link produces a more significant consequence; the user may be taken to another page which they did not intend to browse to. This interrupts the experience, requiring positive action on the users part to return to the previous page and reattempt to hit the correct link. In some certain circumstances, such an error could produce more significant undesirable outcomes, for example if the above scenario is to be encountered during the completion of an ecommerce transaction or in any further nontrivial context.

A tendency is also noted from the literature to focus almost exclusively on graphical targets when conducting user testing assessing touchscreen accuracy. Again, this is an understandable feature of the investigation which yields useful findings, as users frequently encounter graphical or icon based targets, particularly in touch based interaction. However considering the typical usage of current tablet devices, one notes that web browsing is a common activity and one in which the activation of text based links is also frequently encountered and therefore a fairly fundamental requirement. Despite this, text based links thus far remain largely unexplored in the touchscreen usability literature.

Additionally, suggestions to explore the context, arrangement and density of targets are noted from previous investigations and while there is some evidence of this within the literature, detailed investigation exploring the effects of target size versus target spacing does not appear forthcoming.

The current investigation therefore aims to re-examine the nature of the relationships between target *size*, target *spacing* and the *accuracy* with which a target can be selected, within the context of the latest generation of the tablet device. Also of significance, the current investigation aims to investigate performance not just in terms of correct hits, but also explore how the above factors influence the rate of background hits versus incorrect target hits. Moreover the current investigation also intends to investigate both textual and graphical targets, to determine if the type of target has implications for any of the above.

Finally, the current study intends to determine at which sizing and spatial configurations targets become easy (or indeed difficult) to reliably select; and also seeks to explore which of the factors of size or space produces a more profound effect on target selection accuracy.

2 Method

2.1 Participants

The current study employed an opportunity sample (n = 24) recruited through convenience sampling, incorporating subjects of varying age (mean = 29.58, standard deviation = 11.13), gender (58.3% male and 41.7% female), ethnicity and occupation. All subjects were also asked to self-rate their level of experience with touchscreen devices on a 5-point ordinal scale; both regarding their use of smartphone or PDA sized devices (defined for the purpose of this study as a device with a touchscreen size up to 5 inches) and larger touchscreen use (touchscreens greater than 5 inches). Subject's touchscreen experiences varied from *daily* to *never*, however the vast majority of subjects used smaller touchscreen devices on a daily basis (p = 22, 91.7%). Regarding use of larger touchscreen devices, more variance occurred however the majority had at least some experience with their use (p = 21, 87.5%) with the most frequent response being that they had used such devices *once or twice* (p = 68, 33%). Despite this variance in experience, all subjects data was included owing to the very simple nature of the task and a brief training period which was introduced to familiarize subjects with the nature of the screens.

Limited criteria for selecting participants was defined and adhered to, this consisted of a requirement for all participants not to be affected by any condition which may significantly impair visio-perceptual or motor abilities required to complete the tasks. All participants also either spoke English as a first language or were competent in the use of written and spoken English. Finally, subjects did not receive any direct financial incentive for participating in the study, and were made aware of their ethical rights.

2.2 Design

As stated, the primary aim of the current investigation was to explore the effect of two variables which may significantly impact a users touchscreen performance, where performance is determined by correct hit rate, incorrect hit rate and background hit rate. The variables to be investigated were (i) the size of targets, and (ii) the level of spacing between each target. Evidence has been presented to suggest each of these is an important factor in determining touchscreen performance, however the nature of the relationships between these variables and user performance/accuracy, particularly within the context of current tablet devices, has not previously been explored in detail.

An important additional consideration, as discussed, was the type of target that should feature in the investigation; whether targets of a text-based nature (representative of hypertext links encountered in web browsing) or graphical nature (representative of the icons often encountered in mobile operating system and application user interfaces) should be incorporated. As both types of target are frequently encountered, it was deemed necessary to study both of these targets in the current investigation.

In order to study users touchscreen performance with respect to these variables, a repeated measures design was devised whereby each participant was asked to proceed through a number of different screens which presented each type of target in a variety of configurations of varying size and space. Initially, the number of screens developed and the range of size and spacing configurations were determined by the experimenter. A brief pilot design was then undertaken on a small number of subjects to verify and further inform the range of sizes and spacing configurations to administer to subjects in the experiment proper.

The brief pilot phase resulted in some minor alterations, and from this it was determined that the included text sizes would be 8, 10, 12, 14, 16 pt text across line spacings of 100, 125, 150, 200 and 250 percent standard line spacing (based on the CSS linespace attribute). Icon sizes ranged from 6x6 pixels up to 42x42 pixels, rising in 6 pixel increments and icon spaces ranged from 1 to 6 pixels in 1 pixel increments.

The independent variables manipulated in the current investigation were therefore:

(i) Type of target
- with two levels; *text-based* or *graphical*

(ii) Size of targets
- with five levels for the text-based targets and seven levels for the graphical targets

(iii) Spacing between targets
- with five levels for the text-based targets and six levels for the graphical targets

The dependent variable in the current investigation was touchscreen performance, which comprised of three levels;

(i) Correct target hit
- the subject hit the target requested

(ii) Incorrect target hit
- the subject hit a different or adjacent target to that which they had been requested to hit

(iii) Background hit
- indicating the white space between targets was hit

2.3 A Note on the Practical Construction of the Interfaces

As indicated, the tablet computer selected for the purpose of this study was the Apple iPad 2. While there are a number of reasons this particular device was deemed to be a suitable candidate for this investigation (primarily its prototypical form as discussed previously, but also market position as well as the quality of touch sensing it provides), this selection did however have implications for the creation of the interfaces on which the user testing was conducted, which resulted in an unusual approach for producing the interfaces.

The design of the practical component of the investigation required a number of unique screens to be generated which were to be presented in sequence to participants. Due to the number of screens required, the level of customization required for each of the screens, and the intention to capture data on the device, the optimal solution would have been to create a native application. Unfortunately this was deemed to be unfeasible due to a number of constraints (including technical expertise on the part of the experimenter, and the relative complexity and cost, time and monetary, required to develop a native iOS application at the time of writing).

After further researching additional potential solutions and consultation with several individuals including the project supervisor, it was established that the most suitable course of action was to construct the interfaces as a website or web application, so as to avoid the complications involved in developing any form of local application and then 'sideloading' it onto the iPad.

The interface which was presented to participants of the current study therefore takes the form of a number of linked webpages (67 experimental 'target' screens, not including an additional number of training, instructional and supporting screens) which are constructed using HTML and CSS. Each target screen features three types of link, which correspond to one of the following three conditions; (i) *Correct*- the successful selection of the indicated target, (ii) *Incorrect*- the selection of another target adjacent to the indicated target, and (iii) *Background*- the selection of the space between any of the targets.

The entire visible area of each target page is clickable, with a tap on any region of the page corresponding to one of the above three conditions. A PHP script (residing on the server) then recorded for each screen which of the three types of link had been activated, before redirecting the browser to the next page in the sequence. The output from the PHP script was a log in the form of a plain text file, listing each screen, the users input (termed correct, incorrect or background) and also a record of the time and session (used to link each participants data with the paper-based demographic questionnaire administered).

As discussed, target sizes carry more meaning when standard units of measurement are applied, however for practical purposes, target sizes were determined by CSS attributes based on availability. Standard measurements for targets in terms of millimetres are however attached in the appendices.

2.4 Materials, Resources and Apparatus

The following materials and apparatus were used in the conduct of the user testing;

- 1 x Apple iPad 2 tablet computer: The iPad 2 was selected on the basis that it is (at the time of conducting the study) the most recent iteration of what has by far been the most commercially successful current generation tablet series to date, Apple's iPad. By using this platform, the current study therefore was more likely to be representative of the majority of tablet users and experiences.

- The experimental screens: As described previously, these were hosted online and the experiment was conducted using the default Safari web browser on the iPad. Instructional screens and a brief training session were also incorporated into the online portal through which the experiment was conducted, further details of which are provided in the appendices.

- A 3G/WiFi data connection was required to provide internet access to the above.

- A paper based questionnaire and consent form: Demographic information for each of the participants was obtained via a paper questionnaire, and paper-based written consent was obtained from each participant.

A number of additional software packages were required for various aspects of the investigation, including web development tools, productivity software and statistical analysis tools.

The experimenter also wishes to acknowledge with gratitude the support of several individuals who assisted with technical advice and practical assistance in generating the screens used and the mechanism for collecting data, as credited in the acknowledgements section.

2.5 Procedure

As previously described, all participants were recruited through the use of opportunity or convenience sampling. Initially, the format and purpose of the study were briefly described to all participants, who were then asked to read a standardised, more detailed introduction to the study on the iPad itself. Ethical information including subjects' rights as a participant was also presented at this point. Upon agreeing to take part in the study, participants were asked to complete a brief demographic questionnaire and provide written consent of their willingness to participate. The experimenter then noted the current time and a unique identifier on to the demographic questionnaire, which allowed this information to be linked to the subjects data during data analysis at a later stage.

Subjects were then given the opportunity to ask any questions before and after a brief training session, which merely presented a few screens of the type used in the live testing session, so as to familiarize subjects with the 'look and feel' of the interface and the touch operation of the tablet.

Subjects then proceeded to progress through the screens, attempting in each case to hit the clearly identifiable requested target. Upon tapping on each screen, the users input was automatically logged and the browser was directed to the next page in the sequence. As noted, the sequence contained a total of 67 screens. Upon completing the last screen, the browser was directed to a page which signified the end of the testing session, thanked the participant for their time, and displayed experimenter contact information (a hardcopy of this information was also available upon request).

Upon completion of the data gathering, the log file containing subjects response information was checked for errors, linked to participants demographic information (which was separate from the consent form and so not personally identifiable) and then carefully entered into a preformatted data sheet for later analysis.

2.6 Hypotheses

The main experimental hypotheses for the current investigation stated that a clear association will be notable between subject's performance and each IV of text size, text spacing, icon size and icon spacing. Although in some cases it may be possible to make directional predictions based on intuition (for example, that correct hits will increase as target size increases), for the purpose of conservative and open investigation the formal hypotheses remain two-tailed.

3. Results

The dependant variable within the current investigation was user performance in selecting the targets, which consisted of three levels corresponding to a users possible 'hit states' (correct target hit, incorrect target hit, background hit). Of these three levels, particular attention was paid to the variable of primary interest; that of incorrect target hits. The independent variables comprised of type of tagret (textual or icon), size of the targets presented, and spacing between the targets presented.

Owing to the substantially differing nature of the two types of target as discussed previously, the raw data was split and analyses for textual versus icon-based targets were run seperately.

3.1 Text-based targets

The data from the textual target screens were further seperated to consider the two further independent variables (target size and spacing between targets) in isolation.

Table 1 and Figure 6 (below) express in terms of mean percentage the rate of correct target hits, hits of the incorrect surrounding targets, or background hits. The independent variable of text size in this case contains five levels with text sizes ranging from 8px to 16px. From the graphical presentation of the data, one may infer a possible weak positive association between text size and correct hits, and a potential negative association in the case of incorrect hits. This would suggest that in the current investigation at least, the range of text sizes which were used did not introduce major variance effects in terms of observed user performance, although at least minor effects with regards to correct and incorrect target hits are noted.

Table 1: Performance (in terms of Mean Percentage) over Text Size

Text Size	Correct	Incorrect	Background
8	78.3	18.3	3.3
10	82.5	16.7	0.8
12	82.5	12.5	5
14	85.8	11.7	2.5
16	88.3	10	1.7

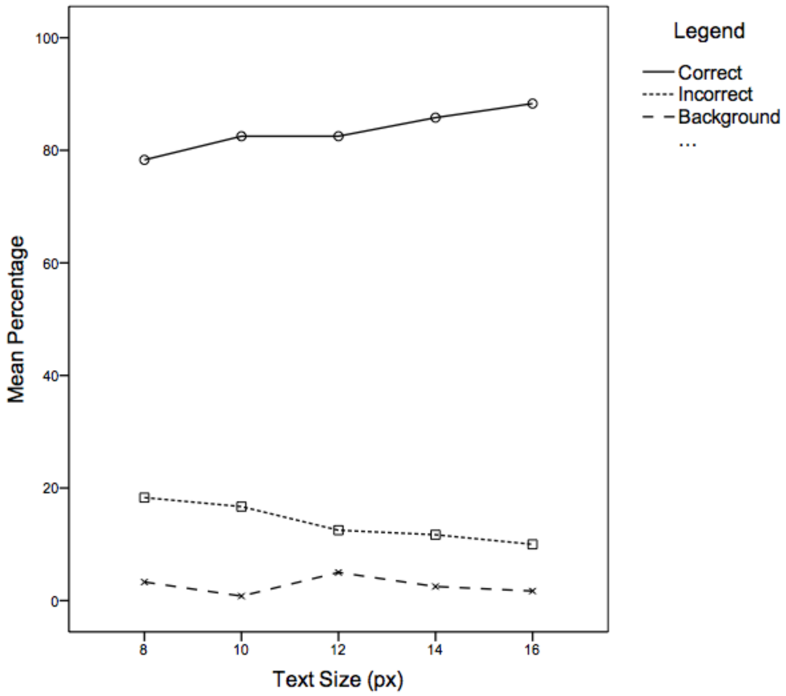

Figure 6: Graphical Depiction of Performance over Text Size

In order to further explore any associations between text size and subject performance, correlative analyses were performed on the data for correct target hits and incorrect target hits. The analyses suggested there was a positive linear relationship between correct hits and text size; $r(118) = .187$, $p = .041$, and a negative linear relationship between incorrect hits and text size; $r(118) = -.180$, $p = .049$.

Due to both correlations yielding significant associations at the $p < .05$ alpha level, further regression analyses were conducted. The regression model for the positive relationship between correct hits and text size was significant; $F(1, 118) = 4.280$, $p = .041$ however the association was weak with text size accounting for only 3.5% of the variability in correct scores ($r^2 = 0.035$), producing a model upon which one is unable to base strong predictions. Similarly, the regression model for the negative relationship between incorrect hits and text size was also significant; $F(1, 118) = 3.972$, $p = .049$ however again the association was weak, with text size this time accounting for only 3.3% of the variability in correct scores (r2 = 0.033).

Table 2 and Figure 7 (below) present again in terms of the mean percentage of hit state achieved, the effect of varying vertical line spacing between the text targets. The independent variable of text spacing in this case again contains five levels which represent line spacing configurations ranging from standard (100%) up to an increased spacing of 250%. The data initially appear to show a trend suggesting level of correct hits increases as spacing increases, however in the case of the textual target screens with the greatest level of spacing between targets, performance appears to drop substantially and the number of incorrect target hits increases. This anomoly is so pronounced, it seems unlikely to be a result of chance, which would therefore suggest an unidentified variable having a significant effect on the data.

Table 2: Performance (in terms of Mean Percentage) over Text Spacing

TextSpace	Correct	Incorrect	Background
100	67.5	30	2.5
125	79.2	19.2	1.7
150	88.3	6.5	4.2
200	95	3.3	1.7
250	87.5	9.2	3.3

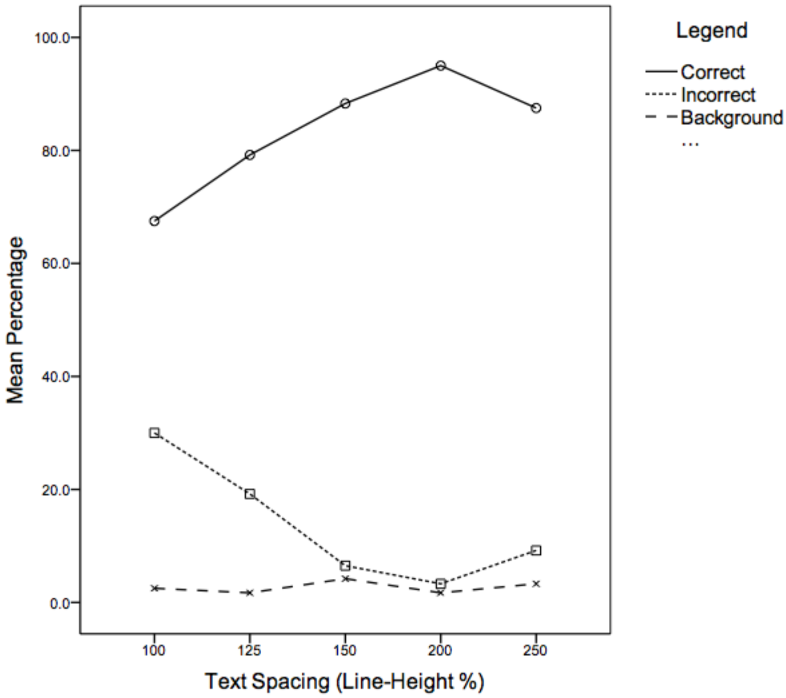

Figure 7: Graphical Depiction of Performance over Text Spacing

Due to the significant effect of the unknown influence described above, it was deemed inappropriate to perform inferrential analyses on the data for text spacing, as such an exercise would unfortunately provide no insight as to the source of the anomoly. This point is however further discussed in the following chapter.

3.2 Icon based targets

The data from the icon based target screens was again split to consider the effects of target size and spacing between targets seperately.

Table 3 and Figure 8 (below) present the mean percentage of correct target hits, incorrect target hits and background hits in relation to a number of different icon sizes. In this case, the independent variable of icon size had seven levels, with icons ranging in size from 6 pixels squared up to 42 pixels squared in 6 pixel increments. From the line graph, one may infer a potentially significant trend whereby the mean percentage of hits of the correct target rises dramatically as the target size increases up to the icon size of 24 pixels, upon which increase plateaus to an extent, continuing to rise only very slowly. Likewise, potential negative associations between icon size and incorrect and background hits are visible. None of these potential relationships appear linear however.

Table 3: Performance (in terms of Mean Percentage) over Icon Size

Icon Size	Correct	Incorrect	Background
6	13.9	18.1	68.1
12	49.3	4.9	45.8
18	70.8	2.1	27.1
24	91.7	0.7	7.6
30	93.8	0.7	5.6
36	95.8	0.7	3.5
42	97.2	0.7	2.1

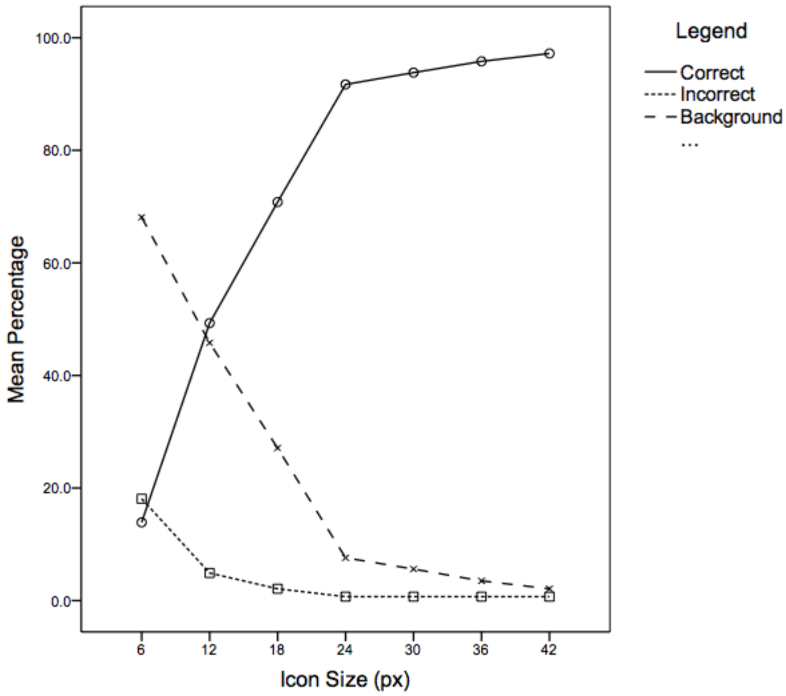

Figure 8: Graphical Depiction of Performance over Icon Size

Due to the nonlinear nature of the association effects observable in figure 8, a correlation or linear regressive analysis of the data was deemed inappropriate. Unfortunately however, attempts to explore the associations using nonlinear regression analysis did not yield any insightful conclusions. Informal analysis based on the descriptive presentation of the data (above) is however provided in the following chapter.

Table 4 and figure 9 (below) again shows the mean percentage of correct, incorrect and background hits in relation to a number of different icon spacings. In this case, the independent variable of spacing between icons had six levels, with icon spacings ranging in size from 1 to 6 pixels in 1 pixel increments. No clear trends are observable between mean percentage of correct target hits or background hits and icon spacing. Again, findings presented below would suggest further investigation is required in order to evidence or explore any relationships between these performance conditions and icon spacing. There does however appear to be a potential relationship between incorrect item hits and icon spacing, which is further explored below.

Table 4: Performance (in terms of Mean Percentage) over Icon Spacing

IconSpacing	Correct	Incorrect	Background
1	78.6	10.1	11.3
2	73.2	6.5	20.2
3	70.8	4.8	24.4
4	69	2.4	28.6
5	75	0	25
6	72.6	0	27.4

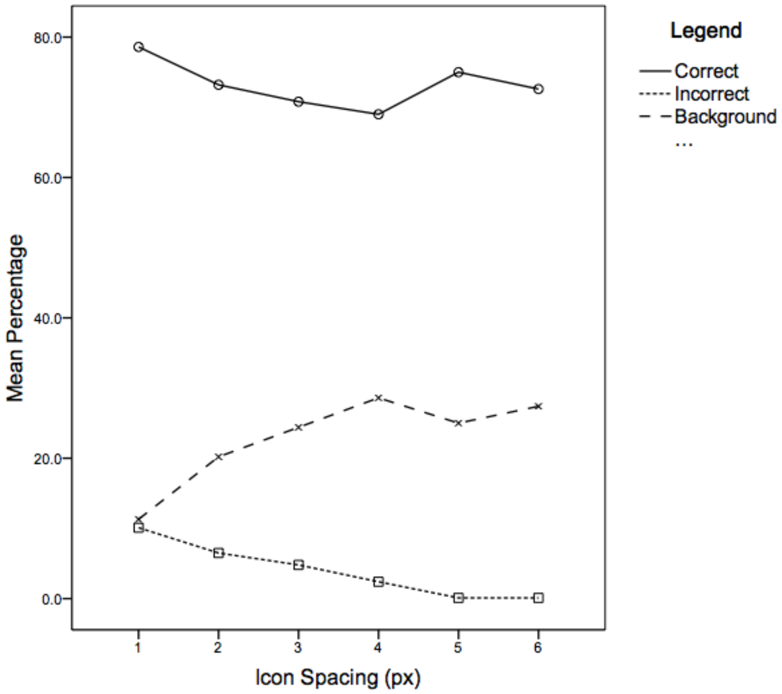

Figure 9: Graphical Depiction of Performance over Icon Spacing

In order to further explore any association between icon spacing and subject performance, correlative analysis was again performed on the data for incorrect target hits. The analysis suggested there was a negative linear relationship between correct hits and text size; $r(142) = .465$, $p < .001$.

Due to the correlation suggesting a significant effect, further regression analyses were conducted. The regression model for the negative relationship between incorrect hits and icon spacing was significant; $F(1, 142) = 39.278$, $p < .001$ however the association was relatively weak with icon spacing accounting for 21.7% of the variability in correct scores ($r^2 = 0.217$), producing a model from which it would again be unwise to derive predictions.

4. Discussion

As described, the present investigation sought to re-examine the accuracy of touchscreens within the context of current tablet devices. In particular, a number of items were of interest including target size and target spacing, type of target, and incorrect versus background as well as correct target hits. In order to investigate these variables, a repeated measures design was devised whereby each participant was asked to proceed through a number of different screens which presented each type of target in a variety of configurations of varying size and space, with participant's hit data for each screen being recorded and analysed. The independent variables in the current investigation were therefore type of target, target size and target spacing, while the dependent variable was performance, as expressed in terms of correct, incorrect or background hits.

The data was split in order to conduct meaningful analyses for each of the independent variables in isolation, and while a number of associations were found, the study also produced some unexpected results. Analysis and discussion of the specific findings is presented below.

4.1 Findings for the Text targets

As presented, statistical analyses revealed there were indeed relationships both between text size and correct hits, and text size and incorrect hits, confirming the experimental hypotheses for these levels of the dependent variable. From this one may infer that targets became easier to hit as they increased in size, while the chance of selecting an incorrect target reduced; although naturally one cannot infer cause and effect from this type of correlative analysis. The results obtained with regards to the extent of the effect of text size on user performance however would suggest that any associations here are surprisingly modest in terms of strength. Regression analyses indicated that while these effects were unlikely to be a result of chance (given the significance of the alpha values) the actual effect sizes of the associations were small (as evidenced by the low coefficients). There did not appear to be any association between the number of background hits observed and the changing text sizes, suggesting that the text size made no difference as whether or not subjects hit the space between targets.

While statistically significant associations were observed between text size and two of the three levels of performance, one may have expected text size to exert yet a stronger influence over user performance levels. Ultimately however, there was not very much variance in user performance on the basis that even when the very smallest text sizes were presented, subjects were surprisingly accurate at acquiring these small targets. This conflicts with the data obtained during a brief pilot, in which success rates for hitting the correct target on a text size of 8px were low. It would appear therefore that the current investigation would have indeed benefited from including a greater range of text sizes, in particular featuring text sizes below 8px. One also notes however that even at a relatively generous text size of 16px, subjects did not reach close to the ceiling in terms of correct hits, with performance not reaching 90% accuracy at the largest text size. This clearly indicates there is still room for improvement in ensuring text links are able to be reliably selected on current tablet devices.

The results regarding text spacing indicate an effect that was not anticipated and is not explained by the data alone. There appears initially a fairly strong association between text spacing and both correct and incorrect hits, which one might expect; this would have implied that as targets are spaced further apart, they become easier to hit and the chance of hitting an incorrect target reduces. However the assumption that this is a straightforward association is violated by the data for the largest spacing, which seemingly presented subjects with more of a challenge. The anomaly here, as noted in the results, is unlikely to be a consequence of chance alone as percentages expressed in figure 7 correspond to averages across five trials at a spacing of 250% for all 24 participants.

This would seemingly suggest that even if associations are present (which one cannot infer since this was not tested), an external variable seemingly has a pronounced effect on selection performance. Unfortunately the data presented here alone cannot explain why, once targets become a certain distance away from surrounding targets, accuracy decreased. Further investigation would be required to explore this effect, and to see if a pattern emerges when even larger spacing is introduced. One potential account for this effect may be a methodological concern which is described later; the location of targets on screens used in the current setup. Merely speculating, one other possible account could be that when targets appeared to be spaced so far apart, subjects tended to exert a lower amount of effort in acquiring them, which in turn reduced performance. Were such an effect to be the result of either of these potential accounts however, one might expect background hits to have increased, as opposed to incorrect target hits.

As stated, unfortunately given all the available information, one can still ultimately only speculate as to the cause of this unexplained anomaly, and further investigation would be required to explore and account for this effect. Due to fact that an unknown variable appears to exert such influence on this data, any inferential analysis was deemed unsuitable as to declare any associations would be discount the observed effect, yet we do not have justification to dismiss the anomaly as we have no indication to its cause. Correlating the data would not provide any insight with respect to this.

4.2 Findings for the Icon targets

From figure 8, one can infer a clear positive relationship between correct target hits and icon size, with correct hit mean percentage ranging from 13.9% for an icon size of 6x6 to 97.2% for an icon size of 42x42. Likewise, a negative relationship between background hits and icon size appears to be present, with background hit mean percentage rates dropping from 68.1% for the smallest target to 2.1% for the largest. This would appear to fall in line with predictions of associations, and suggests that as target size increased, so to did the number of correct hits. Likewise, smaller targets appeared to result in a greater number of background hits, however as target sizes increased these background hits reduced substantially. However one also notes from the graphical presentation of this data that these associations are clearly not linear, and as such cannot be meaningfully correlated in the same way as was conducted for the other datasets. One notes that although hits of incorrect targets seem to drop, even at their peak in the case of the smallest targets, they only account for 18.1% of hits suggesting subjects were much more likely to hit the background space as opposed to an incorrect target.

The data for icon size therefore would suggest that the size of targets is a significant factor in determining performance, with greater sizes leading to improved accuracy, a finding consistent with results from several previous investigations and with Fitts' law, both of which suggest target size can be assumed as a predictor of accuracy. As one would expect based on this, instances of error are subsequently reduced as target size is increased. Notable also is the observation that incorrect target hits reduced to a very low level once target icon size grew above 24x24, which equates to a visible target size of approximately 3.65mm.

With regards to the data for icon spacing, in terms of correct hits and background hits at least, a clear picture does not emerge and any trend effects do not appear pronounced. Interestingly, the highest mean percentage of correct hits was observed for the icons spaced most closely together (78.6% correct at an icon spacing of 1px), which would appear to contrast with the findings noted from the text target data, where the smallest spacing measure resulted in the lowest rate of correct hits. As with the findings from text-space however, again the data initially appear to show a potential emerging trend only to seemingly defy any such trend past a given point (in this case, an icon spacing of 4px). This effect requires further investigation in order to be meaningfully accounted for. In the case of hits of incorrect targets however, the figure 9 does show a potential linear association with text spacing, which subsequent statistical analyses confirm. As with the text size data however, while the association appears unlikely to be a result of chance, the strength of the association is again shown to be only modest, with text spacing accounting for only 21.7% of performance variation based on the regression model, raising questions as to what accounts for the remaining variability.

One finding from text spacing therefore falls in line with expectations; that as spacing increases between targets, the chance of users selecting the incorrect target appeared to reduce, the effect of a statistically significant negative association between incorrect hits and target spacing. Informally, one might also suggest that the likelihood of hitting background spacing may increase as background spacing is increased, however further investigation would be required to explore if this is indeed the case, as the data presented here may be consistent with this, but does not indicate this with any significance or clarity.

4.3 Accounting for the difference between text and icon target types

One additional observation based on the data obtained in the current investigation is that it appears differences between the types of target may exist, given the inconsistent findings between text size versus icon size, and text spacing versus icon spacing. Upon noting this from the data and carefully reanalyzing the screens used in the experimental setup, one significant difference between the text targets and the icon targets was noted, which may help to account for both the variability within conditions, and the inconsistencies between the text and icon findings.

It appears that the findings from the text targets and icon targets are unsuitable for comparison due to a touchscreen 'stabilisation' mechanism aimed at improving touch accuracy (as described in the introduction), which was effective in the case of the text based targets however not effective for the icon based screens.

As described previously, the experimental setup involved the creation of a series of web pages, with text targets constituting standard hyperlinks while icon targets simply consisted of images, with all screens presented using the built in Safari web browser. The software however appears to apply correction to hits based slightly off-target for the hypertext links, which had the effect of superimposing active selection areas on the text targets which were in actual fact larger than the visible areas of the text links. This effect was however 'hardcoded' out of the graphical or icon based target screens, a result of specifying fixed item sizes with both targets and background effectively on the same 'layer'. The result of this mechanism is that text links presented to participants had in effect an invisible buffer, which accommodated for imprecise input, while icon based screens did not.

This finding very likely goes some way to accounting for the high accuracy rates observed with regards to text target selection, and may further have had implications for minimizing hits to the background (since targets were effectively 'easier to hit' than the background). The discovery of this corrective mechanism and its impact on the design provides further support for the assertion that text targets of an even small size than 8px should have been included in the study in the absence of the ability to control for this potentially significant variable.

4.4 Methodological Criticisms

The current investigation, it should be noted, is not without several methodological concerns which may to varying degrees have exerted some influence on the data obtained and as such are discussed in the current section.

One such concern for example is the location of targets on the screen. A conscious decision was taken early in the design process to present the clusters of targets on each screen in different screen locations, for two primary reasons: (i) because typical activities and interactions undertaken on tablets do no revolve around only focusing on one particular area of the screen, and (ii) to reduce the repetitive nature of the task and force users to adjust to and acquire each individual target, as opposed to hovering their finger above only one section of the screen. The specific locations at which targets were presented was not however considered to be of significant interest, the only stipulation being that for each screen, the primary target was not placed immediately at a screen edge. Due to the testing being conducted as part of a repeated measures design, it was also not considered necessary to randomize screen locations as no learning effect could occur. In retrospect however, it is noted that the location at which targets appear on the screen is a variable which may potentially introduce undesired effects, and better methodological practice would have been to randomize locations which would have served to remove any effects introduced by placing any target in a specific location.

Similarly and again on the basis that the current investigation employed a repeated measures design, it was not deemed necessary to vary the sequence with which screens were presented to users. While the order of screen presentation was deliberately mixed (determined by the experimenter) so as to not present subjects with all of the text targets followed by all of the icon targets for example, or all targets of a certain size in a row (under which a learning effect may have ensued), the order in which targets were presented was the same for each subject. Again, as this is a repeated measures design, no learning effect could occur as a result of sequence, however based on the above assertion that location was an uncontrolled variable, presenting the target screens in the same order could have exacerbated any location effect and therefore counterbalancing should also have been employed in this instance. For example, if the action of readjusting hand posture from target *a* located lower on the screen up to target *b* located higher on the screen is likely to introduce error, the static sequence of presentation of the interfaces may result in target *b* yielding an artificially high error rate.

One notes that with hindsight, it would also have been valuable to conduct a more thorough pilot investigation, which would more likely have suggested a need for a greater variety of (particularly text) target sizes and spacings. As noted in the results and discussion, users achieved remarkably high levels of accuracy with even the smallest text sizes, which means unfortunately the data presented here only show ‘part of the picture’, for example one cannot derive from the results presented here at which size text becomes truly difficult to target, one may only infer that this size would be less than 8px.

Finally, as acknowledged previously, one further potentially significant variable that was not controlled was the stabilization mechanism which was present for text targets but not icon targets. Ideally, this variable would have been removed by controlling for or simply removing this mechanism from the text targets, which would have enabled the comparison of text data directly with icon data. However since such comparisons were not performed in the current investigation, this does not constitute a significant weakness.

4.5 Directions for Future Work

As indicated in the results, some of the data from the current investigation appears to show effects and variables not currently accounted for, in particular the anomaly discussed which was observed at a text spacing of 250%. Findings from the current investigation raise several such specific questions, and even some of the effects here which did seem to yield significant correlations are not fully explored, such as the nonlinear associations observable in the case of icon size, and also the shape of the association between performance and text sizes smaller than 8px or larger than 16 px. Future investigation could therefore yield more insight or provide more conclusive explanation of some of the effects observed in the current investigation.

One useful extension of the current investigation might also be to take a measure not only of hit state, but as with many comparable investigations, also study the time taken by subjects to hit each target. This would provide at least an initial indication of the effort with which subjects acquire certain targets and could therefore provide some insight into exploring the theory proposed earlier that as targets reach a certain point of perceived ease, subjects invest less effort in acquiring them.

One further potential avenue of research might also be regarding the effect of location on performance, specifically in the context of tablet devices. Several investigations have explored target location within different contexts, for example with one handed or thumb based interaction on mobile devices. It has been determined by previous investigation that due to the biomechanics of the thumb or hand, certain postures (e.g. typical one handed thumb based use) produce implications for performance based on location. While these postures are not frequently adopted in typical tablet usage, the extent to which location influences performance remains unexplored in this new context.

Additionally, a natural progression from the current investigation would be to explore the effectiveness of different selection strategies or proposed solutions, or indeed develop further solutions to address the issues of accuracy and occlusion which clearly still persevere.

4.6 Conclusion

The current investigation sought to explore the effects of target size and target spacing (both with regards to text and icon based targets) on touchscreen performance within the context of current tablet devices. A comprehensive literature review revealed that though comparable investigation had been undertaken with regards to other devices, findings may potentially not be transferable, and evidence of investigation into the usability of the latest generation of tablet devices is currently lacking from the literature. The current investigation featured a repeated measures design whereby participants were asked to select both text and icon targets of varying size and spatial configurations on a number of screens, with hit state (correct target hit, incorrect target hit or background hit) measured as the dependent variable. Results revealed some trends which translated to statistically significant associations, however these associations were also found to be relatively weak in terms of predictive power due to low effect size. Some unidentified effects were also observed which appear to merit further investigation. Ultimately, findings suggest that associations do exist between the size and spacing of targets and user performance, however these relationships are complex and other factors are clearly present.

4.7 Personal Reflection

One gets the impression that perhaps the current investigation was slightly ambitious with regards to its design, the complexity of which was not fully appreciated until data analysis was considered! The objectives of the current investigation however do not seam unrealistic or unfeasible, although ultimately perhaps a more streamlined process and design could have been generated, given more forethought. While the methods and measures chosen appear relatively simplistic, the design resulted in a large volume of data (the datasheet for the raw data contains some 72 variables across 24 cases, with multiple levels for each variable), and without a full grasp of the design, data analysis proved to be the most significant issue encountered in the current project.

The literature review was perhaps similarly overambitious, with many topics juggled. The introduction was drafted from scratch twice, as a result of the first effort lacking coherence. The literature search, while not absolutely exhaustive, was thorough, and did feel like a useful and even enjoyable exercise.

The results obtained are perhaps slightly disappointing, as limited findings can be drawn from a dataset which is ultimately fairly inconclusive. The data analyses revealed that even though the influence of chance was limited (owing largely to the experimental design and sample size) effect sizes were small which resulted in regression models which, though significant, at the same time carry little weight. The most significant looking data obtained, as described, came in the form of a nonlinear association which given a very limited grounding in statistics, proved impossible to meaningfully interpret using inferential statistics.

Time management was perhaps one of the most valuable lessons of the current project, and also one that ties into it: planning ahead. These are vital skills, which the current project has demonstrated the importance of (for they are most greatly appreciated from a distance).

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Index of Appendices

Appendix A: Project Definition for MSc in Human Centred Systems

Name:	Jonathan Day
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Contact Phone number	07926826416
Project Title:	Examining Target Selection Accuracy for Small Interface Items on Tablet Computers
Supervisor:	Dr George Buchanan

Background and Rationale

Within the past twelve to eighteen months, tablet or 'slate' computers have attracted significant interest and attention in the media, owing to a raft of product launches. The growth of this market, driven largely by Apple's *iPad*, has been extensively documented by industry analysts and hailed a 'revolution' by countless internet and media publications. With one source projecting forecasts for tablet shipments at 44.6 million units for the year of 2011 (IDC, 2011), the tablet appears set to become a commonplace internet and media consumption appliance.

Tablet computers are characterized by one defining common feature; their utilization of a large, high resolution touchscreen, which functions both as an output display and an all-purpose input device for user interaction. The vast majority of current and upcoming tablets support multitouch gestures and are designed primarily to accept input not by stylus, but from one or more fingers. While this format does provide some desirable advantages, significant challenges are also presented primarily in the form of accuracy and error rates (particularly when smaller items are targeted), and occlusion owing to the obscuring of screen content by a user's fingers during interaction (Lee, 2010).

The issues identified above have been documented and explored extensively in the context of touchscreens on smaller, more portable devices (such as smartphones and PDAs), as well as traditional tablet PCs and touchscreen-equiped computers. However, the current iteration of the tablet device has a number of key differences in terms of screen technologies, typical applications and contexts of use which separate recent and future tablets from other similar devices.

Summary of Existing Literature

Due to the recent re-emergence and reinvention of the tablet form factor (which is still a rapidly evolving space), empirical investigation into the usability of the very latest tablets appears lacking from the academic press. However the issues of touchscreen accuracy and target occlusion have been investigated at length on a number of other devices as described previously, from which one can derive some of the potential usability factors uniquely arising from touchscreen operation.

Sears and Shneiderman (1991) provide an account of early investigation into the usability of touchscreens, and indeed even in a favourable usage scenario (i.e. a laboratory environment, and using a fixed and stable touchscreen computer) identify and discuss "the problem of returning multiple pixel locations for a single touch". Work from as far back as 1985 is cited which expresses concern over the accuracy hit which can potentially result from user's finger sizes. Ultimately however, Sears and Shneiderman report touchscreens to be a largely accurate and intuitive method of interaction, and advocate their suitability in a number of contexts, suggesting advantages including "…simple operation, ease of learning, rapid performance, and potentially low error rates".

Investigation into the specific problems arising from touchscreen interaction does not all support the notion that touchscreens provide high precision input however. Lank and Saund (2005) express clearly how even in pen-based systems, there is often a clear division between "user intent" and a user's "literal stroke". With regards to finger-based touchscreen interactions with smaller mobile devices, a recent trend in touchscreen smartphones has lead to a wealth of new studies identifying some of the difficulties presented in terms of accuracy (Kwon et. al., 2010; Chen et. al. 2010; Park & Han, 2010) and occlusion (Lee, 2010; Kwon et. al., 2009).

While the literature presents a mixed picture with regards to the perceived operability and accuracy of touchscreens, one methodological observation is noted which appears to be largely unexplored. Traditional experimental paradigms for establishing touchscreen accuracy have frequently required users to select targets in relative isolation; that is to say largely surrounded by areas of white space. Given the limited screen space which tablets are able to offer, it may be valuable to explore target selection accuracy in a more realistic and busy context; an interface which features numerous items.

Proposed Project Description

The proposed investigation intends to re-examine the aforementioned touchscreen interaction issues specifically in the context of current multitouch tablet devices, with a view to focusing on the extent to which the complexity and 'clutter' of an interface affects a users touchscreen performance.

The investigation therefore has the following primary objectives:

- To present a review of current literature into the accuracy of touchscreen interaction

- To explore and provide a detailed account of the issues which arise when users are required to target and select small objects in crowded interfaces using current tablet devices

- To establish whether the complexity of the interface affects the ease and accuracy with which it can be operated

- To discuss findings, implications and suggest where potential opportunities for improvement may be found

In terms of the practical approach adopted to satisfy these objectives, the following is proposed:

- An extensive literature search and detailed literature review to present current understanding of the problem domain

- The preparation and execution of user testing designed to establish target selection and accuracy on a recent tablet using a number of varied interfaces (with metrics such as error rates and types, timing data, and any additional potentially illuminating information such as subjective feedback). Data is to be captured preferably using software on the device itself, however alternatively via video recording and observation.

- Detailed exploration of the resultant data; with statistical measures employed to identify any themes or relationships regarding performance and interface complexity

- An evaluative presentation of the process and findings, and a discussion referring back to published literature with any suggestions for future investigation identified

Perceived Value

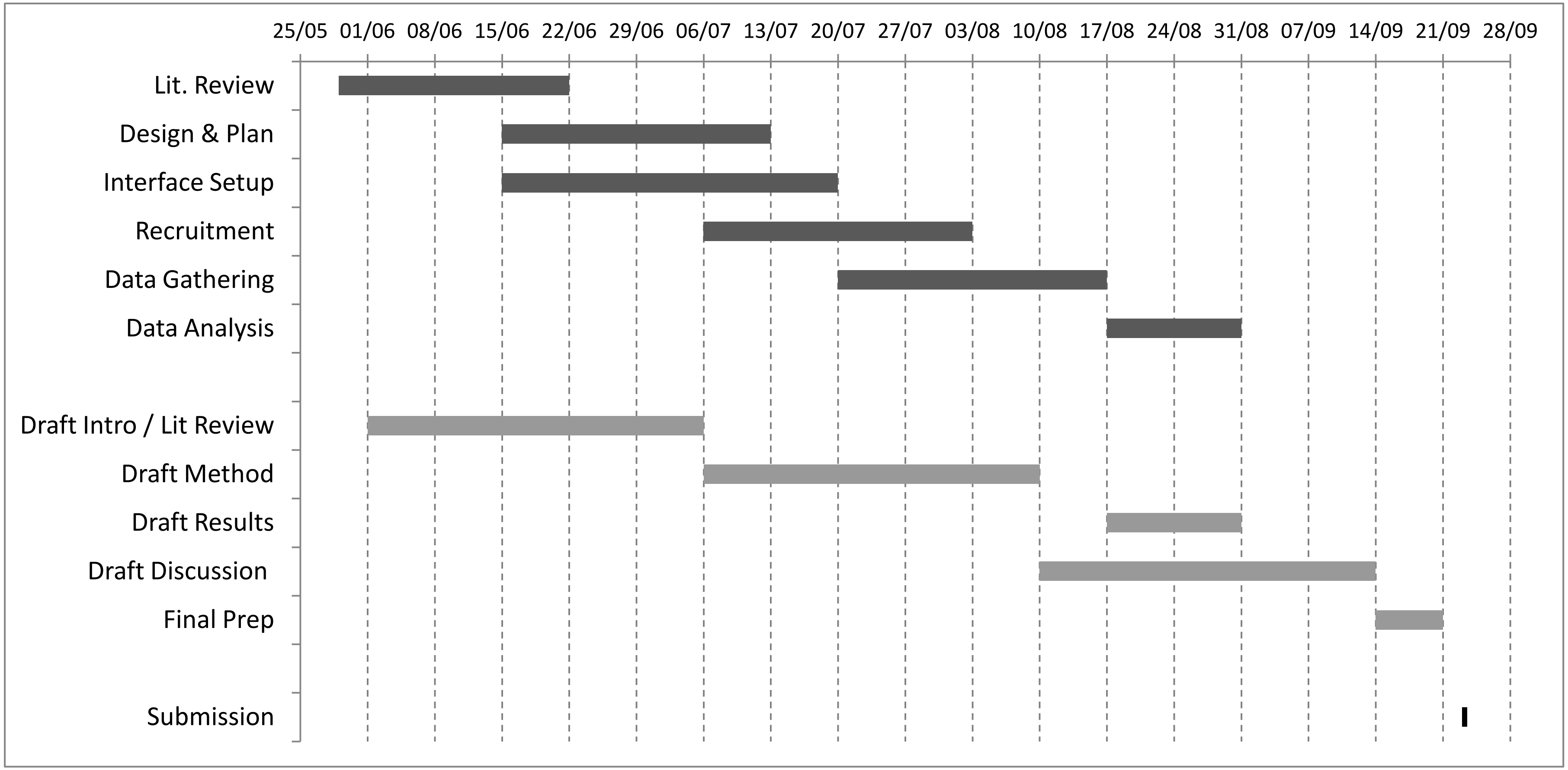
In addition to contributing to an active and substantial research community in this area (including publishers and organisations such as *CHI, Transactions in Computer Human Interaction and MobileHCI*) a number of other parties could potentially benefit from the proposed investigation, including device manufacturers (such as *Nokia, Apple, Samsung* etc.), mobile developers (such as *Adobe*), web developers/publishers and ultimately users of future tablet and touchscreen devices.

Assessment of Feasibility

The proposed investigation does provide some potential challenges in terms of researcher skill set and resources. The course of action suggested does assume a level of technical competence in the setup of the interfaces for the tablet device, and with regards to the collection of data. While the investigator is to an extent familiar with these issues (having conducted previous investigative work using tablets), a significant amount of time must be allocated to the preparation of the user testing, as is suggested in the work schedule detailed below. Should the preferable automated data gathering not prove ultimately feasible however, as previously mentioned, data capture could alternatively be conducted via video recording.

With regards to the equipment needed, naturally a tablet device is the single most significant non-standard item which is required. The selection of the particular tablet to be used has not yet been made, due to the imminent release of several models, however no problems are anticipated in acquiring a suitable tablet in the near future. Should this however prove to be a problem, permission has been sought and access to a tablet device is possible via the project supervisor.

Work Schedule



The above workplan indicates proposed timescales for the various activities both concerning the practical conduct of the usability testing (shown above) and the creation of the accompanying report document (shown below).

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Appendix B: Raw Data

project data COMPLETE ordered.sav

	p#	age	gender	touchusebelow5	touchuseabove5	size06space01	size06space02
1	1	23	female	Daily	Once or Twi...	Background	Incorrect
2	2	23	male	Daily	Once or Twi...	Incorrect	Background
3	3	22	male	Daily	Once or Twi...	Background	Incorrect
4	4	23	female	Occasional ...	Daily	Background	Background
5	5	23	male	Daily	Occasional ...	Incorrect	Background
6	6	23	male	Daily	Never	Background	Background
7	7	63	male	Daily	Once or Twi...	Incorrect	Background
8	8	57	female	Daily	Occasional ...	Background	Background
9	9	23	female	Daily	Occasional ...	Background	Background
10	10	39	male	Daily	Several Time...	Correct	Incorrect
11	11	31	female	Never	Never	Background	Incorrect
12	12	42	male	Daily	Occasional ...	Incorrect	Incorrect
13	13	35	female	Daily	Several Time...	Incorrect	Background
14	14	36	male	Daily	Once or Twi...	Background	Background
15	15	32	male	Daily	Daily	Incorrect	Correct
16	16	27	male	Daily	Several Time...	Incorrect	Background
17	17	29	female	Daily	Once or Twi...	Background	Background
18	18	21	female	Daily	Once or Twi...	Incorrect	Background
19	19	23	female	Daily	Daily	Incorrect	Background
20	20	24	male	Daily	Several Time...	Incorrect	Background
21	21	23	male	Daily	Daily	Incorrect	Background
22	22	23	male	Daily	Daily	Correct	Correct
23	23	23	male	Daily	Once or Twi...	Incorrect	Incorrect
24	24	22	female	Daily	Never	Background	Correct

project data COMPLETE ordered.sav

	size06space03	size06space04	size06space05	size06space06	size12space01	size12space02	size12space03
1	Background	Background	Correct	Background	Correct	Correct	Correct
2	Incorrect	Background	Background	Background	Correct	Correct	Background
3	Incorrect	Incorrect	Background	Background	Correct	Background	Correct
4	Background	Background	Background	Background	Correct	Background	Correct
5	Background	Background	Correct	Background	Correct	Correct	Correct
6	Incorrect	Incorrect	Background	Background	Incorrect	Incorrect	Incorrect
7	Background	Background	Background	Background	Background	Background	Incorrect
8	Background	Background	Background	Correct	Correct	Background	Correct
9	Background	Background	Background	Background	Incorrect	Correct	Background
10	Background	Background	Background	Background	Correct	Correct	Background
11	Correct	Correct	Background	Background	Correct	Correct	Background
12	Incorrect	Background	Background	Correct	Correct	Background	Background
13	Background	Background	Background	Correct	Correct	Correct	Background
14	Background	Background	Background	Background	Correct	Correct	Background
15	Background	Background	Correct	Background	Correct	Correct	Correct
16	Background	Incorrect	Background	Background	Correct	Background	Correct
17	Background	Background	Background	Background	Correct	Background	Background
18	Background	Background	Background	Background	Background	Background	Incorrect
19	Background	Background	Background	Correct	Correct	Correct	Correct
20	Correct	Background	Correct	Background	Correct	Correct	Correct
21	Incorrect	Background	Correct	Correct	Correct	Correct	Background
22	Correct	Background	Correct	Background	Correct	Correct	Background
23	Background	Background	Background	Background	Correct	Background	Correct
24	Background	Background	Background	Background	Incorrect	Correct	Correct

project data COMPLETE ordered.sav

	size12space04	size12space05	size12space06	size18space01	size18space02	size18space03	size18space04
1	Correct	Correct	Background	Correct	Correct	Correct	Correct
2	Correct	Correct	Background	Correct	Incorrect	Background	Correct
3	Background	Background	Background	Correct	Background	Background	Correct
4	Correct	Background	Correct	Correct	Correct	Background	Correct
5	Correct	Background	Correct	Correct	Correct	Correct	Correct
6	Background	Background	Background	Correct	Correct	Correct	Correct
7	Background	Background	Correct	Background	Background	Correct	Correct
8	Background	Correct	Background	Correct	Correct	Correct	Background
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10	Correct	Correct	Correct	Correct	Background	Background	Correct
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20	Background	Background	Correct	Correct	Correct	Correct	Background
21	Background	Background	Background	Correct	Background	Background	Background
22	Background	Correct	Background	Correct	Correct	Correct	Correct
23	Background	Background	Background	Incorrect	Background	Correct	Background
24	Background	Background	Background	Correct	Correct	Correct	Correct

project data COMPLETE ordered.sav

	size18space05	size18space06	size24space01	size24space02	size24space03	size24space04	size24space05
1	Correct	Correct	Correct	Correct	Correct	Correct	Correct
2	Correct	Background	Correct	Correct	Correct	Correct	Correct
3	Background	Background	Background	Correct	Correct	Background	Correct
4	Correct	Correct	Correct	Correct	Correct	Correct	Correct
5	Background	Correct	Background	Correct	Correct	Correct	Correct
6	Background	Background	Correct	Correct	Background	Correct	Correct
7	Correct	Correct	Correct	Correct	Correct	Correct	Correct
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9	Correct	Correct	Correct	Correct	Correct	Correct	Correct
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11	Correct	Correct	Correct	Correct	Correct	Correct	Correct
12	Correct	Correct	Correct	Correct	Correct	Correct	Correct
13	Correct	Correct	Correct	Correct	Background	Correct	Correct
14	Correct	Correct	Correct	Correct	Correct	Correct	Correct
15	Correct	Correct	Correct	Correct	Correct	Correct	Correct
16	Correct	Correct	Correct	Correct	Background	Correct	Correct
17	Correct	Correct	Correct	Correct	Correct	Correct	Correct
18	Background	Background	Correct	Correct	Correct	Correct	Correct
19	Background	Correct	Correct	Correct	Correct	Correct	Correct
20	Correct	Background	Correct	Correct	Correct	Correct	Correct
21	Correct	Correct	Correct	Incorrect	Correct	Background	Correct
22	Correct	Correct	Background	Correct	Correct	Correct	Correct
23	Correct	Background	Correct	Correct	Correct	Correct	Correct
24	Correct	Correct	Correct	Correct	Correct	Correct	Correct

project data COMPLETE ordered.sav

	size24space06	size30space01	size30space02	size30space03	size30space04	size30space05	size30space06
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3	Correct	Correct	Correct	Background	Correct	Correct	Correct
4	Correct	Correct	Correct	Correct	Correct	Correct	Correct
5	Correct	Correct	Correct	Correct	Correct	Correct	Correct
6	Background	Correct	Background	Correct	Incorrect	Correct	Correct
7	Correct	Correct	Correct	Correct	Correct	Correct	Correct
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14	Correct	Correct	Correct	Correct	Correct	Correct	Correct
15	Correct	Correct	Correct	Correct	Correct	Correct	Correct
16	Correct	Correct	Correct	Correct	Correct	Correct	Correct
17	Correct	Correct	Correct	Correct	Correct	Correct	Correct
18	Correct	Correct	Correct	Correct	Background	Correct	Correct
19	Correct	Correct	Correct	Correct	Correct	Correct	Correct
20	Correct	Correct	Correct	Correct	Correct	Correct	Correct
21	Background	Correct	Correct	Correct	Background	Correct	Correct
22	Correct	Correct	Correct	Correct	Correct	Correct	Correct
23	Correct	Correct	Correct	Correct	Correct	Correct	Correct
24	Correct	Correct	Correct	Correct	Background	Correct	Correct

project data COMPLETE ordered.sav

	size36space01	size36space02	size36space03	size36space04	size36space05	size36space06	size42space01
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3	Correct	Correct	Correct	Correct	Correct	Background	Correct
4	Correct	Correct	Correct	Correct	Correct	Correct	Correct
5	Correct	Background	Correct	Correct	Correct	Correct	Correct
6	Correct	Correct	Correct	Correct	Correct	Correct	Correct
7	Correct	Correct	Correct	Correct	Correct	Correct	Correct
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9	Correct	Correct	Correct	Correct	Correct	Correct	Correct
10	Correct	Correct	Correct	Correct	Correct	Correct	Correct
11	Correct	Correct	Correct	Correct	Correct	Correct	Correct
12	Correct	Correct	Correct	Correct	Correct	Correct	Correct
13	Correct	Correct	Correct	Correct	Correct	Correct	Correct
14	Correct	Correct	Correct	Correct	Correct	Correct	Correct
15	Correct	Correct	Background	Correct	Correct	Background	Correct
16	Correct	Correct	Correct	Background	Correct	Correct	Correct
17	Correct	Correct	Correct	Correct	Correct	Correct	Correct
18	Correct	Correct	Correct	Correct	Correct	Correct	Correct
19	Correct	Correct	Correct	Correct	Correct	Correct	Correct
20	Correct	Correct	Correct	Correct	Correct	Correct	Correct
21	Correct	Correct	Correct	Correct	Correct	Correct	Correct
22	Correct	Correct	Correct	Correct	Correct	Correct	Correct
23	Incorrect	Correct	Correct	Correct	Correct	Correct	Correct
24	Correct	Correct	Correct	Correct	Correct	Correct	Correct

project data COMPLETE ordered.sav

	size42space02	size42space03	size42space04	size42space05	size42space06	textsize08space100	textsize08space125
1	Correct	Correct	Correct	Correct	Correct	Correct	Correct
2	Correct	Correct	Correct	Correct	Correct	Correct	Incorrect
3	Incorrect	Correct	Correct	Background	Correct	Correct	Incorrect
4	Correct	Correct	Correct	Correct	Correct	Correct	Correct
5	Correct	Correct	Correct	Background	Correct	Correct	Correct
6	Correct	Correct	Correct	Correct	Correct	Incorrect	Incorrect
7	Correct	Correct	Correct	Correct	Correct	Incorrect	Incorrect
8	Correct	Correct	Correct	Correct	Correct	Background	Correct
9	Correct	Correct	Correct	Correct	Correct	Incorrect	Incorrect
10	Correct	Correct	Correct	Correct	Correct	Correct	Correct
11	Correct	Correct	Correct	Correct	Correct	Correct	Incorrect
12	Correct	Correct	Correct	Correct	Correct	Incorrect	Correct
13	Correct	Correct	Background	Correct	Correct	Incorrect	Correct
14	Correct	Correct	Correct	Correct	Correct	Correct	Correct
15	Correct	Correct	Correct	Correct	Correct	Incorrect	Correct
16	Correct	Correct	Correct	Correct	Correct	Correct	Correct
17	Correct	Correct	Correct	Correct	Correct	Background	Correct
18	Correct	Correct	Correct	Correct	Correct	Incorrect	Incorrect
19	Correct	Correct	Correct	Correct	Correct	Incorrect	Correct
20	Correct	Correct	Correct	Correct	Correct	Correct	Correct
21	Correct	Correct	Correct	Correct	Correct	Correct	Correct
22	Correct	Correct	Correct	Correct	Correct	Correct	Correct
23	Correct	Correct	Correct	Correct	Correct	Correct	Correct
24	Correct	Correct	Correct	Correct	Correct	Incorrect	Correct

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	textsize08space150	textsize08space200	textsize08space250	textsize10space100	textsize10space125	textsize10space150	textsize10space200
1	Correct	Incorrect	Correct	Correct	Correct	Correct	Correct
2	Correct	Correct	Correct	Incorrect	Correct	Correct	Correct
3	Correct	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect
4	Incorrect	Correct	Correct	Correct	Correct	Correct	Correct
5	Correct	Correct	Correct	Correct	Incorrect	Incorrect	Correct
6	Correct	Correct	Correct	Incorrect	Correct	Incorrect	Correct
7	Correct	Correct	Correct	Correct	Incorrect	Correct	Correct
8	Correct	Correct	Correct	Incorrect	Correct	Correct	Correct
9	Correct	Correct	Correct	Correct	Incorrect	Correct	Correct
10	Correct	Correct	Correct	Correct	Correct	Correct	Correct
11	Correct	Correct	Correct	Correct	Correct	Correct	Correct
12	Correct	Correct	Correct	Incorrect	Correct	Correct	Correct
13	Correct	Background	Correct	Correct	Incorrect	Correct	Correct
14	Correct	Correct	Correct	Correct	Correct	Correct	Correct
15	Correct	Correct	Correct	Incorrect	Correct	Correct	Correct
16	Correct	Correct	Background	Correct	Incorrect	Correct	Correct
17	Correct	Correct	Correct	Correct	Correct	Correct	Correct
18	Correct	Correct	Incorrect	Correct	Correct	Incorrect	Correct
19	Correct	Correct	Correct	Correct	Correct	Correct	Correct
20	Correct	Correct	Correct	Correct	Correct	Correct	Correct
21	Correct	Correct	Correct	Correct	Correct	Correct	Correct
22	Incorrect	Correct	Correct	Correct	Correct	Background	Incorrect
23	Correct	Correct	Correct	Correct	Incorrect	Correct	Correct
24	Incorrect	Correct	Correct	Correct	Correct	Correct	Correct

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	textsize10space250	textsize12space100	textsize12space125	textsize12space150	textsize12space200	textsize12space250	textsize14space100
1	Correct	Correct	Correct	Correct	Correct	Correct	Correct
2	Correct	Correct	Correct	Correct	Correct	Correct	Correct
3	Incorrect	Correct	Correct	Incorrect	Correct	Incorrect	Incorrect
4	Correct	Correct	Correct	Correct	Correct	Correct	Correct
5	Correct	Incorrect	Correct	Correct	Correct	Correct	Correct
6	Correct	Correct	Correct	Correct	Correct	Correct	Incorrect
7	Correct	Correct	Incorrect	Correct	Correct	Correct	Incorrect
8	Correct	Correct	Correct	Correct	Correct	Correct	Incorrect
9	Correct	Correct	Correct	Correct	Correct	Correct	Correct
10	Correct	Incorrect	Correct	Correct	Correct	Correct	Correct
11	Incorrect	Correct	Correct	Background	Background	Incorrect	Correct
12	Correct	Correct	Correct	Correct	Correct	Correct	Incorrect
13	Correct	Incorrect	Correct	Background	Correct	Background	Incorrect
14	Correct	Correct	Correct	Correct	Correct	Correct	Correct
15	Correct	Incorrect	Incorrect	Correct	Correct	Incorrect	Incorrect
16	Correct	Correct	Background	Correct	Correct	Correct	Incorrect
17	Correct	Correct	Correct	Correct	Correct	Correct	Correct
18	Correct	Correct	Incorrect	Correct	Correct	Correct	Correct
19	Correct	Correct	Correct	Correct	Correct	Correct	Correct
20	Correct	Incorrect	Correct	Correct	Correct	Correct	Correct
21	Incorrect	Background	Correct	Correct	Correct	Correct	Correct
22	Correct	Incorrect	Correct	Correct	Correct	Correct	Incorrect
23	Correct	Correct	Correct	Correct	Correct	Incorrect	Correct
24	Correct	Correct	Incorrect	Correct	Correct	Correct	Correct

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	textsize14space125	textsize14space150	textsize14space200	textsize14space250	textsize16space100	textsize16space125	textsize16space150
1	Correct	Correct	Correct	Correct	Incorrect	Correct	Correct
2	Correct	Correct	Correct	Correct	Correct	Correct	Correct
3	Correct	Correct	Correct	Correct	Incorrect	Correct	Incorrect
4	Correct	Correct	Correct	Correct	Correct	Correct	Correct
5	Correct	Correct	Correct	Correct	Correct	Incorrect	Correct
6	Incorrect	Correct	Correct	Incorrect	Correct	Correct	Correct
7	Correct	Correct	Correct	Correct	Incorrect	Incorrect	Correct
8	Correct	Correct	Correct	Background	Incorrect	Correct	Correct
9	Correct	Correct	Correct	Correct	Correct	Correct	Correct
10	Correct	Correct	Correct	Correct	Incorrect	Correct	Correct
11	Incorrect	Correct	Correct	Background	Correct	Background	Correct
12	Correct	Correct	Correct	Correct	Correct	Correct	Correct
13	Correct	Background	Correct	Correct	Incorrect	Correct	Correct
14	Correct	Correct	Correct	Correct	Correct	Correct	Correct
15	Incorrect	Correct	Correct	Correct	Incorrect	Correct	Incorrect
16	Correct	Correct	Incorrect	Correct	Correct	Correct	Correct
17	Correct	Correct	Correct	Correct	Correct	Correct	Correct
18	Correct	Correct	Correct	Correct	Correct	Correct	Correct
19	Correct	Correct	Correct	Correct	Correct	Correct	Correct
20	Correct	Correct	Correct	Correct	Correct	Correct	Correct
21	Correct	Correct	Correct	Correct	Correct	Correct	Correct
22	Correct	Correct	Correct	Correct	Correct	Correct	Correct
23	Correct	Correct	Correct	Correct	Correct	Correct	Background
24	Correct	Correct	Correct	Correct	Correct	Correct	Correct

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	textsize16space200	textsize16space250
1	Correct	Correct
2	Correct	Correct
3	Correct	Incorrect
4	Correct	Correct
5	Correct	Correct
6	Correct	Correct
7	Correct	Correct
8	Correct	Correct
9	Correct	Correct
10	Correct	Correct
11	Correct	Correct
12	Correct	Correct
13	Correct	Correct
14	Correct	Correct
15	Correct	Correct
16	Correct	Correct
17	Correct	Correct
18	Correct	Correct
19	Correct	Correct
20	Correct	Correct
21	Correct	Correct
22	Correct	Correct
23	Correct	Correct
24	Correct	Correct

Appendix C: Information Regarding the Screens

As the testing was conducted online, examples of the instructions, training and experimental screens are not included here, however these can be accessed and the entire testing apparatus run through at the following URL:

http://jdd.comli.com

Alternatively, an index of all the experimental screens used along with the sequence in which they were presented is available here:

http://jdd.comli.com/admin.html