CROSS-DISPLAY ATTENTION SWITCHING IN MOBILE INTERACTION WITH LARGE DISPLAYS

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Cross-Display Attention Switching in Mobile Interaction with Large Displays

PhD Thesis

by

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Abstract

Mobile devices equipped with features (e.g., camera, network connectivity and media player) are increasingly being used for different tasks such as web browsing, document reading and photography. While the portability of mobile devices makes them desirable for pervasive access to information, their small screen real-estate often imposes restrictions on the amount of information that can be displayed and manipulated on them. On the other hand, large displays have become commonplace in many outdoor as well as indoor environments. While they provide an efficient way of presenting and disseminating information, they provide little support for digital interactivity or physical accessibility. Researchers argue that mobile phones provide an efficient and portable way of interacting with large displays, and the latter can overcome the limitations of the small screens of mobile devices by providing a larger presentation and interaction space. However, distributing user interface (UI) elements across a mobile device and a large display can cause switching of visual attention and that may affect task performance.

This thesis specifically explores how the switching of visual attention across a handheld mobile device and a vertical large display can affect a single user's task performance during mobile interaction with large displays. It introduces a taxonomy based on the factors associated with the visual arrangement of Multi Display User Interfaces (MDUIs) that can influence visual attention switching during interaction with MDUIs. It presents an empirical analysis of the effects of different distributions of input and output across mobile and large displays on the user's task performance, subjective workload and preference in the multiple-widget selection task, and in visual search tasks with maps, texts and photos.

Experimental results show that the selection of multiple widgets replicated on the mobile device as well as on the large display, versus those shown only on the large display, is faster despite the cost of initial attention switching in the former. On the other hand, a hybrid UI configuration where the visual output is distributed across the mobile and large displays is the worst, or equivalent to the worst, configuration in all the visual search tasks. A mobile device-controlled large display configuration performs best in the map search task and equal to best (i.e., tied with a mobile-only configuration) in text- and photo-search tasks.

Keywords: multi-display environment, distributed user interfaces, multi-device use, device interoperability, smartphones, large displays.

Declaration

I, Umar Rashid, hereby certify that this thesis, which is approximately 40,000 words in length, has been written by me, that it is the record of work carried out by me, and that it has not been submitted in any previous application for a higher degree.

I was admitted as a research student in September 2010 and as a candidate for the degree of Doctor of Philosophy in September 2010; the higher study of which this is a record was carried out in the University of St Andrews between 2010 and 2012, (and in University College Dublin between 2007 and 2010).

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Publications

Some ideas presented in this thesis have already been published in some of the following papers.

[1] RASHID, U., KAUKO, J., HÄKKILÄ, J., AND QUIGLEY, A. Proximal and distal selection of widgets: Designing distributed UI for mobile interaction with large display. In *Proceedings of the International Conference on Human Computer Interaction with Mobile devices and services* (New York, NY, USA, 2011), MobileHCI '11, ACM, pp. 495–498.

[2] RASHID, U., NACENTA, M. A., AND QUIGLEY, A. Factors influencing visual attention switch in multi-display user interfaces: A survey. In *Proceedings of the 2012 International Symposium on Pervasive Displays* (New York, NY, USA, 2012), PerDis '12, ACM, pp. 1–6.

[3] RASHID, U., NACENTA, M. A., AND QUIGLEY, A. The cost of display switching: A comparison of mobile, large display and hybrid distributed UIs. In *Proceedings of the International Working Conference on Advanced Visual Interfaces* (New York, NY, USA, 2012), AVI '12, ACM, pp. 99–106.

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This [smartphone] works fine for many small common tasks but I want my radiologist and air-traffic controllers to be using multiple large high-res[olution] displays.

Ben Shneiderman

Chapter 1

Introduction

The emergence of desktop computers in the 1970s and 1980s began an era of *personal computing* (one computer per person) that is credited for bringing computing into mainstream society and removing the constraints of the established *mainframe computing* (one computer for many people). Interaction with a personal computer has been based on the "desktop metaphor" [113] that signifies a standalone and stationary "box" with a processing unit, and input and output devices connected to the box. Although physically smaller in size than a mainframe computer, a desktop computer still lacked portability.

The breakthroughs in the development of portable devices (such as laptops and smartphones) and the widespread availability of mobile telecommunication technologies facilitated the emergence of *mobile* or *nomadic computing* that enabled users to readily access data anywhere at any time. As a result, today it is possible to avail oneself of many features of computing (e.g., reading online information, exchanging digital contents) while away from the computer desk.

The advances in mobile computing [128] and embedded computing have motivated researchers to develop the notion of *ubiquitous computing* (one person with many computers) that suggests a single user interacting with multiple devices embedded into the environment simultaneously. This vision is centred on the prospect of user interaction spanning across a multitude of devices seamlessly, rather than being restricted to one particular device.

The "one box model" of a computer as embodied in the desktop metaphor [113] of personal computing is becoming outdated [146] as it fails to accommodate the user experience across multiple heterogeneous devices in the emerging paradigms of computing (shown in Figure 1.1). While we have enabling technologies for mobile and ubiquitous computing, we can also consider all the computational elements (including input and output) being individually available to be used as a single ecosystem of interaction. Ongoing research into designing user interface (UI) elements spanning across multiple devices [19, 79, 133] points towards an attempt to fill the "missing link" between the conventional desktop metaphor and the advent of multi-device computing and distributed applications.

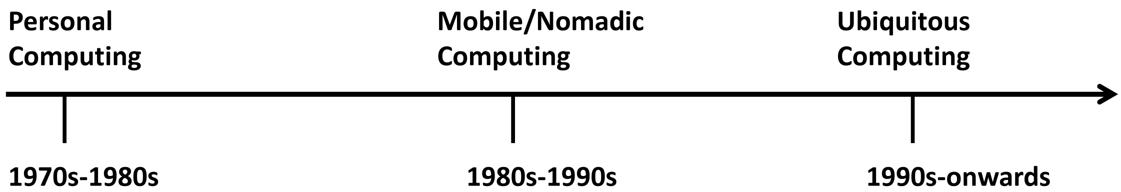


Figure 1.1: Emergence of Different Paradigms of Computing.

1.1 Motivation

Computing devices differ in terms of their input and output capabilities. Researchers have explored the possibility of harnessing the input and output capabilities of different devices to improve user interaction with a multi-device assemblage (e.g., [19, 61]). One particular case is the coupling of small mobile devices with large situated displays [179] to take advantage of the former's personalised interactivity and the latter's presentation space. The distribution of UI elements across different devices can cause switching of visual attention across those devices and that may have an effect on task performance. However, the literature provides little information about the effects on performance due to visual attention switching during interaction across multiple devices.

1.1.1 Mobile Phones: More than Telecommunication

In recent years, mobile phones have become the most pervasive of all computing devices as the worldwide subscribers' base is reported to have already exceeded five billion [26] and is expected to double by 2020 [240], thus foreshadowing a world where mobile phones will soon outnumber humans [25]. Although originally designed for telecommunication, mobile phones equipped with advanced computing ability and features (e.g., camera, networking capabilities, accelerometer) are increasingly being used for day-to-day tasks such as photography, calendar management, e-document reading, games and web browsing [15]. According to an Olswang report in 2011, smartphones are experiencing accelerating rates of adoption: 22% of consumers already have a smartphone, with this percentage rising to 31% among 24–35 year olds [165]. An InMobi survey of 15,000 mobile phone users in 14 countries found that for Internet shopping, users who prefer to use a mobile phone are almost double the number of those who prefer to use a computer [108].

Mobile devices are frequently used in medicine [78], and facilitate the access to patient records [132]. Mobile phones can help students get access to their lessons [148, 188, 253] and stay in touch with their classmates, anytime and anywhere [246]. Inside classrooms, they create a more engaging teaching environment [223]. In the business sector, they allow professionals to work from anywhere, while simultaneously remaining in contact with their colleagues [124]. Users are now able to access e-mails, documents, and the web from their portable device [54] — the tasks that a few years ago would be feasible only on a dedicated personal computer. Moreover, in many developing countries where access to desktop computers is limited, mobile devices are the only means of Internet access [114].

For the purposes of this thesis, the terms *mobile device*, *handheld device* and *mobile handheld device* are synonymous.

1.1.2 Limitations of Mobile Displays

While the portability of mobile devices makes them desirable for pervasive access to information, the small screen size often imposes restrictions on the amount of information that can be displayed and manipulated on mobile devices. While recently there has been a significant increase in the resolution of mobile screens (e.g., Apple iPhone 4™ 's Retina Display has 640x960 pixels), the portable form factor requirements will always place limits on their physical size. More simply stated, small screens are a feature, not a bug of mobile devices. Hence, it is not possible to view large amounts of information simultaneously (due to the low resolution) and adequately (due to the small size) on mobile screens. Researchers have attempted to mitigate this problem by visualizing references to off-screen objects on mobile displays [38].

Being able to attend to more information at once is associated with better perception and comprehension of the information space [173]. Mobile screen users are unable to avail themselves of the performance improvement associated with large displays in tasks such as geo-spatial navigation [183, 231, 232] and visualization [12] tasks. In the words of Ben Shneiderman [138],

"This [smartphone] works fine for many small common tasks but I want my radiologist and air-traffic controllers to be using multiple large high-res[olution] displays."

1.1.3 Large Displays: More than Household Items

The term *large display* is applied to a myriads of displays; they may include *vertical* displays (e.g., television sets, interactive whiteboards, digital signs, wall displays) as well as *horizontal* displays (e.g., tabletop surfaces). The constituent devices may include plasma, Liquid Crystal Display (LCD) or Light-Emitting Diode (LED) monitors, High Definition Television (HDTV) or projectors.

The most pervasive among large displays i.e., the television (TV) set has been a household item of entertainment for decades. However, in recent years, large displays have become commonplace in many locations; these include outdoors (e.g., railway stations, city squares [103]) as well as indoors (e.g., classrooms, workplaces [104, 184]). They have been placed in different social settings: private (e.g., an office), semi-public (e.g., a meeting room) or public (e.g., shopping mall). They provide an effective way of disseminating information and, in addition to their use for advertising and entertainment, are also being used for co-located collaboration [239].

At present, over 2 million SMART Board™ touch-enabled interactive whiteboards are being used, mostly in classrooms, but also in corporate offices, around the world [219]. The retail sector across the world is increasingly making use of digital signs, and the number of these is estimated to rise to 22 million by 2015 [1]. Efforts are being made to integrate Internet connectivity into modern TV sets, thus giving rise to *Smart TV* or *Connected TV*. At the end of 2010, there were 124 million TV sets across the world connected to the Internet and the number of these is estimated to reach 551 million (i.e., 8.9% of global TV sets) by 2016 [49].

1.1.4 Coupling Mobile Displays with Large Displays

Researchers have proposed solutions that support coupling of mobile handheld devices with large displays to create an enhanced user experience. These include using a mobile device as a remote control [14, 101], as a companion device [40] as well as a conduit for exchanging material between displays [34, 45]. Mobile devices can also facilitate interaction with displays that are physically inaccessible and do not provide any means of direct interaction, such as playing pong game with the building-sized Blinkenlights displays [33].

On the other hand, coupling mobile devices with large displays can help overcome the constraints in user experience due to the small screen size of mobile devices [7, 27, 133]. Researchers have presented middleware solutions [171] and interaction techniques [96, 236] to support seamless connectivity between multiple devices. This opportunistic coupling of mobile devices with large displays (among other peripherals) in the environment has given rise to the notion of *device symbiosis* [179].

1.1.5 Distribution of User Interfaces

In order to make the most of multi-device coupling, and also to make its advantages more perceptible, solutions have been introduced that support migration of parts or the whole of a UI across different devices according to the input and output capabilities of these devices [19, 133]. An example of a multi-device user interface is shown in Figure 1.2. This shows a Scrabble game where an iPad serves as a Scrabble board and each iPhone shows the tiles for the player. The separation of UI elements across displays of differing sizes helps overcome the limitations of viewing and interacting with the content on a single display.

Figure 1.2: iPad Scrabble (used with permission from Movie-peg.com).

1.1.6 Attention Switching in Distributed User Interfaces

The literature to date provides little information about the effects on performance due to distributing user interfaces across multiple heterogeneous devices. In particular, not much is known about how the switching of visual attention between a handheld mobile device and a vertical large display affects performance in different tasks. One study [230] showed a detrimental effect of the separation of text in the visual field only if it is also combined with separation in depth, while another shows that users perform a visual search of images better on a single vertical screen than across multiple vertical screens showing different orientations of the same images [76]. These results suggest that the overhead caused by attention switching differs with the type of task being performed. An insight into these issues will help designers understand if when performing a task it is worth distributing user interfaces across multiple displays, and what is the extent of performance gain/loss associated with such distribution.

1.2 Problem Statement

Much of the motivation for this work arises from a literature review in human-computer interaction, experimental psychology and information visualization. The main problem this work tries to address is the effect on task performance of cross-display attention switching in mobile interaction with large vertical displays. Attention is an area widely researched in psychology and neuro-science and it encompasses different modalities such as touch, hearing or sight [5, 267]. Although an attention switch does not necessitate a change in direction of gaze, yet in most cases, the former triggers the latter [259].

In this thesis, the focus is on the performance effects of *cross-display switching*, that specifically refers to the switching of *visual attention* between a handheld mobile device and a vertical large display. The other aspects of visual attention, as well as other modalities of attention, lie outside the scope of the thesis.

The main research problem this thesis addresses is:

How does switching of visual attention between a handheld mobile display and a vertical large display affect a single user's task performance during mobile interaction with large displays?

Considering the scope of this thesis, we break down this high-level question into the following dimensions:

- *Local and remote selection: placement of widgets* for mobile interaction with the large displays:*

  In a task that involves manual selection of multiple on-the-display widgets in series, how does task performance differ while interacting in “no-attention-switch” (widgets on the large display) vs. in “attention-switch” (widgets shown on the large display as well as replicated on the mobile device) configurations of UI elements across a mobile device and a large display?

- *Visual search on mobile, large display and hybrid UIs:*

  How does task performance in visual search tasks differ while interacting in “no-attention-switch” (mobile-only, mobile-controlled-large-display) vs. in “attention-switch” (hybrid) configurations of UI elements across a mobile device and a large display? Three visual search tasks were tested with map, text and photo data.

- *The cost of cross-display switching:*

  How does the overhead caused by cross-display attention switching vary according to the type of the task being performed?

1.3 Research Approach

This work is directed by an experiment-driven constructive research approach. It involves identification of research problems and formulation of hypotheses based on a comprehensive survey of related work. In order to test those hypotheses, prototypes are developed and evaluated through user studies. Based on the experimental results, recommendations

*In this work, a widget refers to an interactive component of a Graphical User Interface (GUI) [140] that can be manipulated to change its visual output or that of the other contents on the display.

for the design of user interfaces distributed across a handheld mobile device and a vertical large display are outlined.

1.4 Thesis Statement

In answer to the problem statement (see Section 1.2), the statement of this thesis is as follows:

In mobile interaction with large displays, selecting multiple widgets replicated on the mobile device as well as on the large display, versus those shown only on the large display, is faster despite the cost of initial cross-display switching in the former. On the other hand, the cross-display switching adversely affects task performance in the visual search of map, text and photo contents replicated across the mobile device and the large display.

1.5 Scope of Thesis

This thesis addresses the question about the performance effects of switching visual attention between a small handheld display and a large vertical display during single-person interaction with the aforementioned displays. For the purposes of the thesis, it is assumed that the infrastructure needed to support network communication between mobile devices and large displays, as well the frameworks to distribute user interfaces across different displays, are readily available or will be available in the near future.

As reflected in Figure 1.3, this thesis neither looks at the underlying frameworks and infrastructures nor at the application areas that involve mobile interaction with large displays.

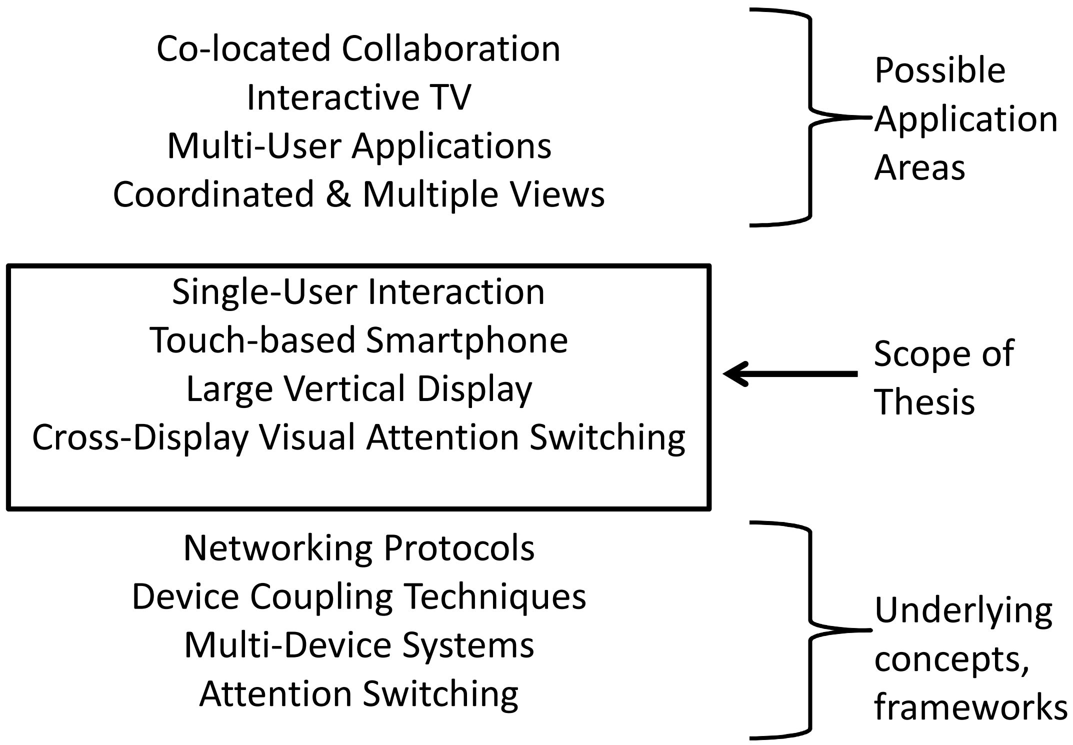


Figure 1.3: Scope of Thesis.

1.6 Thesis Contributions

The contributions of this thesis are as follows:

- *Taxonomy of multi-display user interfaces (MDUIs)*. This thesis introduces a taxonomy based on the factors associated with visual arrangement of UI elements that can affect visual attention switching in user interaction with MDUIs. These dimensions include *display contiguity*, *angular coverage*, *content coordination*, *input directness*, and *input-display correspondence*. A detailed description of this taxonomy is presented in Section 3.2.

- *Analysis of cross-display switching for multiple widget selection*. This thesis explains the empirical evidence for the changing effect of cross-display switching on task performance in the selection of multiple widgets in series, according to the changing difficulty level of the task. The widget selection was made under "no-attention-switch" (i.e., pointing at widgets on the large display) and "attention-switch" (i.e., widgets on the large display replicated and selected on the mobile touchscreen) configurations. The experimental results suggest guidelines for the placement of widgets on a large display or a mobile device to improve performance under different difficulty levels of the task [181].

- *Analysis of cross-display switching for visual search.* This thesis provides empirical evidence of how "no-attention-switch" and "attention-switch" configurations of user interfaces affect task performance, subjective workload and preference in the visual search of map, text and photo contents. The experimental results suggest guidelines for choosing UI configurations for the visual search of different contents. [183].

- *Lessons for practitioners.* Based on the experimental results, this thesis provides guidelines for designers to improve the task performance and enhance the user experience with MDUIs. The guidelines also suggest the experimental conditions where the distribution of the visual output across multiple displays can be detrimental to the task performance.

- *Calculation of cross-display switch overhead.* As a minor contribution, this thesis provides a calculation of the overhead in terms of the time it takes to switch visual attention between a handheld mobile device and a vertical large display. For the widget selection task, the time cost is about 0.64 ± 0.36 seconds; for the map search task, this cost is about 1.8 ± 1.4 seconds with the data simultaneously visible on the mobile display, and 1.8 ± 0.96 seconds with the data simultaneously visible on the large display.

1.7 Thesis Organisation

The thesis is organised as follows:

Chapter 2 defines some terms that are used in the rest of the thesis, and provides an overview of multi-device usage and emerging computing paradigms that envisage an integrated user experience across heterogeneous devices. In this chapter, we discuss approaches towards the design of user interfaces for multi-display systems and highlight some issues of human vision and perception, as well as characteristics of displays, that can be helpful in understanding the human interaction with multi-display user interfaces (MDUIs). We discuss navigation patterns supported by different displays and relate the scope of this thesis to the attention switching associated with the continuum of the navigation pattern under consideration.

Chapter 3 provides an overview of the taxonomies and classifications in the existing literature that are applicable to MDUIs and introduces a taxonomy based on the factors associated with the visual arrangement of UI elements that can affect visual attention switching during user interaction with MDUIs. For each factor, the existing multi-display systems are classified and the relevance to cross-display switching is explained.

Chapter 4 presents an empirical comparison of the task performance for selecting multiple widgets in a "no-attention-switch" vs. "attention switch" condition. The "no-attention-switch" condition is reflected in the Distal Selection (DS) technique that uses a mobile pointer to zoom-in to the region of interest and select the widgets on the large display. The "attention-switch" condition is reflected in the Proximal Selection (PS) technique that involves pointing at the large display and transferring the zoom-in view of the highlighted region of the large display onto the mobile touchscreen for selections thereafter. The task performance, subjective workload and preference with both interaction techniques are discussed, the calculation of cross-display switching time in multiple widget selection task is provided and recommendations for designers are outlined.

Chapter 5 provides empirical evidence of how different configurations of input/output across mobile and large displays affect task performance, subjective workload and preference in visual search tasks. The "no-attention-switch" condition involves mobile-only and mobile-controlled-large-display, while the "attention-switch" condition involves hybrid configuration i.e., visual output being available on both the mobile device and the large display. The tasks tested involved the visual search of map, text and photo contents. The performance differences across different UI configurations are analysed, the calculation of cross-display switching time in the map search task is provided, and recommendations for the design of MDUIs are presented.

Chapter 6 summarises the contributions of the thesis based on the findings presented in Chapters 2–5. It concludes following a discussion about possible directions for the future work.

If I have seen further, it is by
standing on the shoulders of giants.

Isaac Newton

Chapter 2

Background

Devices with computing capacity and visual output (i.e., displays) are increasingly making their way into everyday life. Users are progressively shifting from using a single personal computer to interacting with a wider range of computing devices (e.g., laptops, tablets, mobile phones, media players, e-book readers) [59, 258]. The proliferation of computing devices has created opportunities to make different applications and services readily accessible on multiple devices. For example, it has become commonplace to play videos, check emails and read documents not just on desktop computers but on mobile phones and tablets as well. Researchers are also trying to support interaction *across* multiple devices in order to take advantage of the strengths and overcome the limitations of each device, thus resulting in an enhanced user experience. Examples include *asynchronous* multi-device interaction such as accessing web pages on a desktop computer and resuming them on a mobile device [43, 120], as well as *synchronous* multi-device interaction such as simultaneously playing Scrabble on iPhone and iPad [211].

As discussed in Chapter 1, the classical Graphical User Interface (GUI) model based on a “desktop metaphor” [113] was designed for interaction with input and output devices attached to a single computing device unit. With the increasing prevalence of computing, situations now arise when tasks are performed with user interface elements residing in physically and visually disjointed devices, such as browsing a webpage on a large display and controlling the browsing operation on a handheld device [19]. Efforts are underway to provide explicit support for designing user interfaces across multiple devices [18, 19, 61]. Ongoing developments of multi-device operating systems (e.g., Meego [142], Tizen [243], Microsoft Windows 8™ [264]) are meant to pave the way for an integrated user experience across heterogeneous devices.

This research draws much of its inspiration from the state-of-the-art research on systems that support interoperability and user interaction across multiple devices. In this chapter, we define some terms that are frequently used in the rest of the thesis (see Section 2.1). We report on some user studies on multi-device usage (see Section 2.2). We discuss computing paradigms that envisage the phenomenon of integrated user experience across heterogeneous devices (see Section 2.3) and approaches towards the design of user interfaces for multiple displays (see Section 2.4). We discuss some issues of human vision and perception that can be helpful in understanding human interaction with Multi-Display User Interfaces (MDUIs) in Section 2.5. We explain how these issues relate to task performance using large displays (see Section 2.6). After discussing the attention switching associated with navigation patterns supported by different multi-display systems (see Section 2.7), we conclude this chapter.

2.1 Definitions

In this thesis, we aim to explore the performance effects of attention switching during mobile interaction with large displays, much of the work here having been inspired by the relevant research in multi-device interoperability, multi-display environments, and multi-device user interfaces. As there is some overlap of terms used in the thesis and the same terms used in a different context, it is prudent to define them explicitly to ensure clarity and avoid any confusion or misunderstanding. This section contains definitions of some terms frequently used in the thesis.

2.1.1 Multi-Device Environment

A *multi-device environment* refers to the computing system that supports simultaneous interaction between multiple computing devices. The distinguishing feature of a multi-device environment is that the execution of a task *must* span multiple devices. For example, a mobile phone used to control the cursor on a desktop computer constitutes a multi-device environment. However, writing a text message on the mobile screen while playing a media file on a computer does not fall into the category of a multi-device environment.

2.1.2 Multi-Display Environment

Hutchings et al. [105] coined the term "Distributed Display Environment" (DDE) to refer to the "computer systems that present output to more than one physical display". In this thesis, the term *multi-display environment* (MDE) is used to refer to the said systems.

MDEs may include multiple screens connected to a single computing device (e.g., Nintendo DS), or a logical composition of single-displays, each connected to a different computing device (e.g., SharedNotes [82]). Hence, a multi-display environment may be a single-device or a multi-device environment. Similarly, a multi-device environment may or may not classify as a multi-display environment. For example, a *Nike + iPod* system that supports exchange of data between a shoe sensor and an Apple iPod™ device is a multi-device environment, but not a multi-display environment. On the other hand, SharedNotes [82] is both a multi-device and a multi-display environment. iRoom [111] is another example of a multiple display environment (MDE) that comprises of personal devices such as laptops and shared devices such as large vertical displays to provide a virtual workspace.

Much of the research in multi-device environments overlaps with, and is relevant to, that in multi-display environments as well. Figure 2.1 shows some examples to clarify the association between multi-device and multi-display environments.

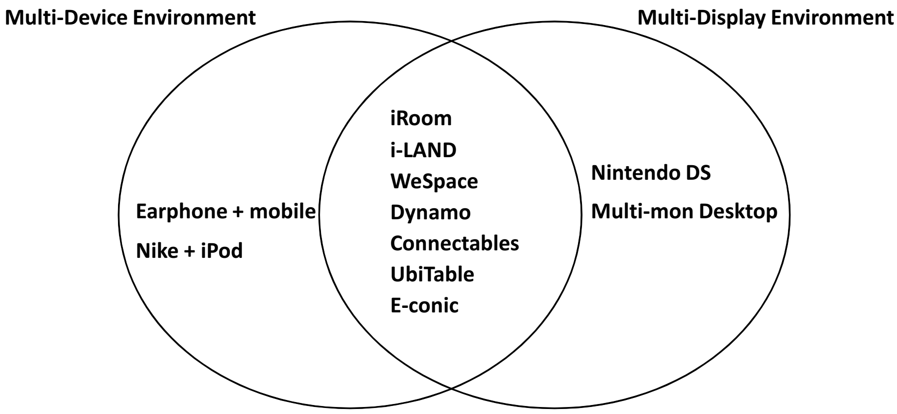


Figure 2.1: Multi-Device and Multi-Display Environments.

2.1.3 Device Interoperability

Interoperability refers to the ability of different systems or devices to work together. In the context of computing, O'Brien and Marakas [163] defined it as "Being able to accomplish end-user applications using different types of computer systems, operating systems, and application software, interconnected by different types of local and wide area networks."

In this thesis, interoperability is defined as the ability of a computing device to have seamless (and synchronous) access to applications and data across multiple devices to accomplish a task.

2.1.4 Multi-Display User Interface

A *multi-display user interface* (MDUI) refers to the configuration of user interface elements (i.e., input and output) across multiple displays in a multiple-display environment. MDUIs are built using computing frameworks and technologies that support device interoperability.

In accordance with the definition of a multi-display environment, the visual output of an MDUI is to be shown on two or more physical displays, while the input may be provided to only one display or all displays may share a common input. For example, a projector phone system supports an MDUI with the input provided on the mobile device and the output shown on both the mobile device and the projection surface. An in-depth description of the taxonomy of MDUIs is given in Chapter 3.

2.2 Usage of Multiple Devices

In recent years, researchers have reported on the experiences of *multi-device users* (MDUs) i.e., the people who regularly use multiple computing devices. In 2008, a study of 27 people from academic and industrial research labs found them to be using more than five computing devices on average [59]. The MDUs identified managing information across devices as the most challenging aspect of the multi-device usage and welcomed the idea of seamless data exchange across different devices [59, 167].

The trend of using multiple computing devices is no longer confined to researchers and academics. Studies by Microsoft Advertising identified about 33 million Americans [258] and 19 million Europeans [257] to be *multi-screen consumers*. A "multi-screen consumer" [258] is defined as an adult in the age group of 18–64 years who uses a TV, computer, and smartphone, and also accesses the Internet at least 23 times each week using both the computer and the smartphone. In 2010, a survey of 1200 of these consumers across the US found evidence of widespread engagement in activities across multiple screens. As stated in [258],

"Multi-Screen Consumers, who used to turn to specific screens for specific activities, are increasingly engaging in activities across multiple screens. Convergence occurs as the functional benefits of each screen come together. Individual activities, from social networking to playing games to watching news highlights, are no longer restricted to a single screen."

Although the capabilities of different computing devices are increasingly merging, the emergence of a single "do-it-all" device is far from appealing. Comparing such a hypothetical megafunctional device to a Swiss Army knife, Don Norman [195] remarked: "When one machine does everything, it in some sense does nothing especially well, although its complexity increases."

This suggests that instead of replacing multiple special-purpose devices by a single omni-purpose device, a synergy of the former is more promising for improving user interactions in many situations [210]. This implication remains a prime motivation for the research on supporting interoperability among devices.

2.3 Computing Paradigms for Device Interoperability

The Merriam Webster Dictionary [143] defines a *paradigm* as "a philosophical and theoretical framework of a scientific school or discipline within which theories, laws, and generalizations and the experiments performed in support of them are formulated". The Oxford English Dictionary [168] defines it as "a world view underlying the theories and methodology of a particular scientific subject".

This section provides a brief overview of some emerging computing paradigms that emphasise the interconnectivity and interoperability of multiple devices as their core concepts.

2.3.1 Ubiquitous Computing

Ubiquitous computing (abbreviated as *ubicomp*; also known as pervasive computing) presents the vision of seamless interaction among multiple computing devices embedded into everyday life [255]. Mark Weiser, the pioneer of ubicomp vision, proposed three basic forms for ubicomp devices as follows:

- *Tabs.* Wearable centimetre-sized devices. Smartphones and portable media players (e.g., Apple iPod™) can be included in this category.

- *Pads.* Handheld decimetre-sized devices. Laptops, netbooks and tablets (e.g., Apple iPad™ , HTC Flyer™ , Samsung Galaxy™) are included in this category.

- *Boards.* Metre-sized interactive display devices. Desktop computer, digital whiteboards and large displays are included in this category.

In the words of Mark Weiser [255],

"*Prototype tabs, pads and boards are just the beginning of ubiquitous computing. The real power of the concept comes not from any one of these devices; it emerges from the interaction of all of them.*"

Due to the proliferation of computing devices of various form factors, as well as the increasing support for their interconnectivity and interoperability, the vision of ubicomp is gradually coming closer to reality. A thorough investigation of ubicomp enabling technologies is beyond the scope of this thesis.

2.3.2 Activity-Based Computing

Activity-Based Computing (ABC) is a paradigm within Ubiquitous Computing that focuses on the *activity* of the user to define interaction with computers [20]. In activity-based computing, the basic computational unit is no longer the file (e.g., a document) or the application (e.g., a word processor) but the activity that aggregates various computational services and data resources, and may include more than one participant (see Figure 2.2).

A user can initiate, suspend, store, and resume one's computational activity on any computing device in the infrastructure at any time, and share it among several persons as well. ABC allows continuation of tasks across different computing devices and adapts the task to the computational resources of each device [21]. For example, high fidelity X-ray images can be shown on a wall-size display but a low-fidelity interface appears when the same task is resumed on a PDA. A detailed explanation of the ABC framework and the deployment of ABC-based experimental prototypes to facilitate collaborative work is presented in [21].

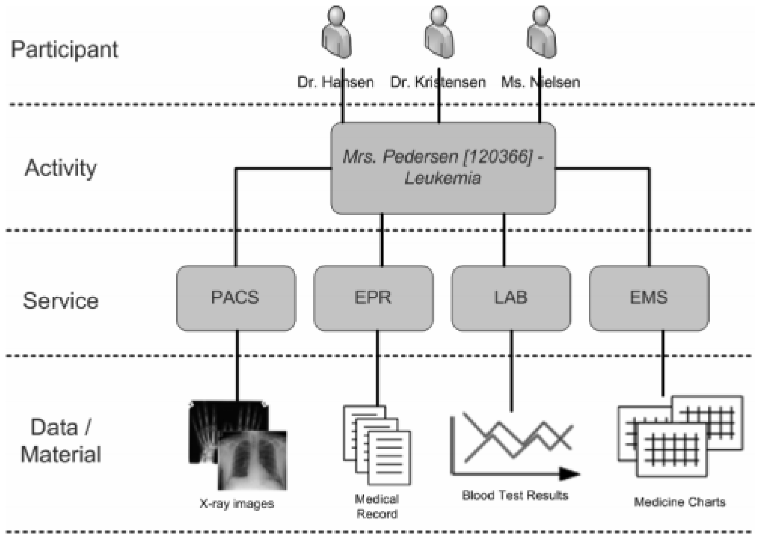


Figure 2.2: A computational activity aggregates a set of computational services, data resources and users (used with permission from [21]).

2.3.3 Recombinant Computing

Recombinant computing [158] is an approach to software infrastructures that aims at supporting *serendipitous* interoperability i.e., the ability of devices and services within Ubiquitous Computing to access one another without having any prior knowledge of each other. It advocates the design of computing entities bearing in mind the consideration that they might be used in multiple ways, in different situations, and for different purposes [158].

This approach has been realised in the Speakeasy framework [157] that supports the provision of user interfaces on multiple platforms. For example, the PDA shown in Figure 2.3 allows for manipulation of a presentation slide on a different platform even though the former does not have the software for presentation slides installed on it, and it has no knowledge of projectors or slide shows in the environment. A detailed explanation of the Speakeasy architecture is provided in [157] but is beyond the scope of this work.

Figure 2.3: Speakeasy: A PDA displaying the controller for a PowerPoint viewer running on a projector (used with permission from [157]).

2.3.4 Synergy of Multiple Devices

Below is a brief overview of the notions concerning synergies of multiple devices that appear in the literature.

Device Ensembles

Schilit and Sengupta [210] introduce the notion of *Device Ensembles* that refers to the working of diverse computing devices in concert to give rise to an enhanced user interaction, similar to the ensemble of musicians that achieves a total effect greater than the sum of individual performances. A particular case of device ensembles is reflected in the coupling of mobile devices with large displays that can be used to make the most of input and output capabilities (e.g., the former's easier physical accessibility and the latter's bigger representation space) of each device.

Figure 2.4 shows the emerging ensembles of digital devices in everyday life. A comprehensive discussion of enabling technologies and industry standards for device ensembles is

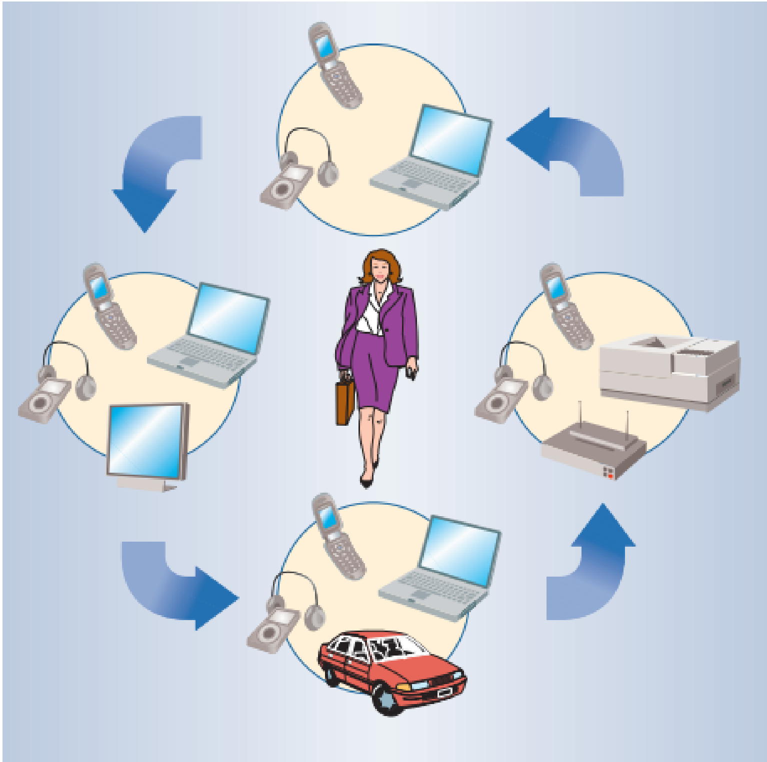


Figure 2.4: Ensembles of digital devices are emerging for common usage models at home, at work, and on the road (used with permission from [210]).

provided in [210], and lies beyond the scope of this thesis.

Cyber Foraging

The notion of *cyber foraging* [8, 208] refers to augmenting the computing capabilities of a resource-poor mobile device by offloading some of the tasks to the computational resources (called *surrogates*) in the environment. A number of systems that support cyber foraging have been proposed [9, 58, 73, 227].

The emphasis of cyber foraging techniques is to enable mobile devices to use the underlying infrastructure or system-level capabilities (e.g., greater processing power, battery life) of fixed computers for the remote execution of applications, and although not originally meant for it, they can support the sharing of the mobile device's visual output on displays connected with the fixed computers.

Device Symbiosis

Borrowing concepts from biology, Raghunath et al. [179] present a notion of symbiosis between handheld devices and large displays in the environment where the former's presentation space opportunistically cause the latter to display content to the user. This notion has been realized in some prototypes. For example, the Personal Server [250] is an auxiliary device that enables a mobile phone to co-opt screens and keyboards of nearby computers through a WiFi connection. Berger et al. [27] present a prototype that allows a user to read an email received on a small handheld display by showing it on large displays.

The notion of device symbiosis is closest to the purposes of this research because it explicitly supports the sharing of UI elements between handheld devices and situated large displays.

2.4 Multi-Display User Interfaces

A case study by Hutchings et al. [106] shows that users are interested in the potential of dividing interfaces across multiple devices mainly based on the input/output capabilities of each device. Current GUI programming toolkits such as Java™ Swing and Microsoft Foundation Classes™ are designed for a single workstation and do not support development of UI across multiple machines. Considering the limitations of the "desktop metaphor" of being tied to a single workstation, researchers have explored alternative models of GUI for a ubiquitous computing environment that take into account its multi-device composition.

Prior to the notion of ubicomp, some researchers provided solutions for migrating the whole or part of a UI from one device to another while preserving the task continuity. Bharat and Cardelli [28] introduced the notion of *migratory applications* that can migrate from one machine to another, along with their UI and application contexts. After migration, they continue on the incumbent host, and the former host may subsequently shut down without affecting the application. However, this notion does not support simultaneous use of an application with its UI elements distributed across different machines.

Coutaz et al. [52] presented a more general framework for migratory applications where migration is intended both as total migration of the application interface as well as splitting it into several parts to be spread over different platforms. Bandelloni and Paterno [19] proposed a solution for runtime migration of Web applications that allows users interacting with an application to change device and continue their interaction from the same point. Their interface generation tool called TERESA also supports *partial migration and synergistic access*, by which a part of the user interface is kept on one device during runtime and the remaining part is moved to another with different characteristics. For example, partial migration allows a user to display videos and photos from a handheld device onto a large display while maintaining control on the former.

Rekimoto [190, 191] proposed the notion of *multiple-computer user interfaces* that consisted of a handheld computer (called M-Pad) serving as a tool palette and data entry palette for the digital whiteboard, as shown in Figure 2.5. Similar to an oil painter holding a palette in his/her hand when painting on a canvas, M-Pad offers an easy way to select tools to manipulate the whiteboard application.

Figure 2.5: A multi-display whiteboard system: digital drawing in the manner of oil painting (used with permission from [190]).

Some experimental prototypes enable the running of specific applications on multiple machines. Johanson et al. [112] presented a solution for allowing a Web page to be seen simultaneously by more than one display. WebSplitter [90] helps split a Web page into personalised partial views for each user and and further splits the partial view into components to be shown on individual devices accessible to the users. WinCuts [234] lets users select regions of interest from a local display and show it to other users on a large display.

The closest to the purposes of this thesis is the notion of the *Distributed User Interface* (DUIs) [65]. DUI refers to any application UI whose components can be distributed across various displays of different computing platforms and can be accessed by different users, co-located as well as remote [61]. DUIs allow for UI elements to be spread over multiple devices/displays/platforms to take advantage of their interaction capabilities, instead of being constrained by that of a single device/display/platform [133].

At present, system support for DUIs remains in its rudimentary stage. Researchers are working on conceptual models [133], software architectures [17] and toolkits [83, 161] to support the generation of DUIs. A detailed discussion of these research endeavours is beyond the scope of this thesis.

2.5 Human Vision and Characteristics of Displays

One aspiration relevant to the effective design of visual interfaces is that it should be based on a sound knowledge of underlying concepts about visual perception. In this section, we present some information about human vision and perception that is pertinent to the design and usage of MDUIs. We will also discuss some characteristics of displays that are relevant to our purposes.

2.5.1 Foveal Vision

The *fovea centralis*, or fovea, is a small area located on the retina in the eye, and is responsible for the sharp vision called *foveal vision*. The human fovea can focus on about 2° visual angle simultaneously. This is the region where 100% visual acuity is attained. A general rule is that the foveal region is almost as wide as one's thumbnail appears at arm's length [251]. This implies that at a normal reading distance (i.e., 30cm), the diameter of foveal region is about 2cm [22].

2.5.2 Peripheral Vision

Peripheral vision refers to the ability to see objects and movement outside of the direct line of vision. Large displays provide more space to utilise the peripheral vision while small displays provide little space to make use of it. The key benefits of exploiting peripheral vision are the greater amount of simultaneously visible data, the broader contextual overview and the awareness of spatial orientation [23, 63, 180].

2.5.3 Visual Field

Visual field refers to the total space visible using the peripheral vision while the eyes are fixed on a central point (i.e., in the foveal region). More simply stated, it stands for the maximum area one can see without moving one's eyes or head. The human visual field typically spans around 200° horizontally and 135° vertically [256]. The foveal vision comprises about 1%-3% of the visual field.

The term "visual field" is often confused with the "field of view" (FOV) but they are not identical. The field of view or "(external) stimulus field" contains everything that causes light to fall onto the retina at any given time. The visual system processes this input and computes the "visual field" (also known as "perceived field") as the output [220]. A large display spans a bigger part of the human visual field and, hence, makes it feasible to view more information at once.

2.5.4 Perceptual Resolution

The *perceptual resolution* refers to the ability of eyes to resolve details in a visual presentation. At a distance of 20 feet (6 metres), human eyes with normal 20/20 vision can distinguish between details as fine as 1 arcminute (i.e., 1/60°) [118]. This angle is also called the *minimum angle of resolution* (MAR). This translates to about 1.75mm being the minimum size of the object that is distinctly distinguishable from a distance of 20 feet.

2.5.5 Useful Field of View (UFOV)

The Useful Field of View (UFOV) refers to the area over which a person can extract information in a single glance [206]. The span of the UFOV varies according to the task and the information being shown [251]. For tasks that require detailed discrimination, such as text reading, the UFOV becomes smaller and the locus of attention is narrowed down. For example, while reading an English script, the UFOV span extends from 3–4 letters to the left of fixation to about 14–15 letter spaces to the right of fixation [185]. On the other hand, for tasks not requiring detailed discrimination, such as visual navigation or detection of large moving objects, the UFOV may extend to 180° [22]. Therefore, in the design of MDUIs, it is important to consider the dominant viewing task while distributing UI elements across displays of different sizes.

2.5.6 Eye Movements

Eye-tracking studies provide valuable information on how the nature of the viewing task influences eye-movement behaviour [185]. Since the foveal region is very small, humans need to make eye movements called *saccades* to view their surroundings. A saccade's duration, i.e., the amount of time it takes to move the eyes, depends on its *amplitude*, i.e., the angular distance it covers. For example, during reading, a saccade usually covers 2° and takes about 30 milliseconds; during scene perception, it usually covers 5° and takes about 40–50 milliseconds [186].

The saccade is ballistic and its destination must be selected prior to the movement. Since the destination usually lies beyond the current foveal region, its selection requires the use of peripheral vision. A saccade is usually followed by a *fixation*, i.e., a period of relative stability when an object can be viewed. The visual information is usually processed and analysed during a fixation [185]. The mean duration of an eye fixation also varies depending on the task. For example, it may last around 225–250 milliseconds during silent reading of an English text and 180–275 milliseconds during a visual search task [186].

Sanders [205] suggested that the visual field can be divided into three regions depending upon whether a visual stimulus can be identified (a) without an eye movement, (b) with an eye movement, and (c) with a head movement. The maximum region a saccade can cover without any head movement is approximately $\pm 55°$ (i.e., the *oculomotor range*) [86], although typically a head movement is involved in any saccade larger than 10° [129].

Eye fixations and saccadic movements are extensively studied in vision science, neuroscience and experimental psychology to determine a person's focus and level of attention [92]. Although an attention shift can happen without an eye movement in simple discrimination tasks [175], the former is closely associated with the latter in complex information processing tasks such as reading and visual search [185].

Fixation durations and saccade amplitudes can vary in different tasks due to the characteristics of the task (e.g., memorization vs. item identification), the type of visual information (e.g., text vs. image), and the density of visual information (i.e., more densely packed items result in longer fixations and shorter saccades) [186]. This implies that the behaviour of eye movements is closely related to the UFOV associated with a particular task (see Section 2.5.5).

User interaction with MDUIs involves an overhead due to the switching of visual attention among UI elements distributed across different displays. Different visual arrangements of MDUIs can also affect the saccade amplitudes, consequently affecting the amount of required eye or head movements, and the time cost of cross-display switching.

2.5.7 Display Characteristics

Some characteristics of display devices affect the viewing experience [265]. For the purposes of this thesis, we divide them into two, i.e., characteristics that determine *how* information appears on the display (e.g., colour, brightness, contrast, refresh rate [265]), and characteristics that determine *how much* information appears on the display (i.e., display size and resolution [254]).

Our exploration is focused on display characteristics that are related to the *how much* factor. For the purposes of this thesis, we assume that the display characteristics related to the *how* factor are held comparable across multiple displays such that their differences are not particularly noticeable by the users. The following subsections discuss some issues related to display resolution, pixel density, pixel size, and viewing distance & angle.

Display Resolution

A screen is typically made up of thousands of tiny dots called *pixels* that collectively illuminate to generate the visual presentation. The *resolution* of a display represents the number of distinct pixels in each dimension. This is usually presented as *width* x *height*, for instance where the units in pixels are "1024x768", it means there are 1024 pixels along the screen's width and 786 pixels along the screen's height, thus 804864 screen pixels in total.

Pixel Density

Another useful measure of a display resolution is called *pixel density* or *pixels per inch* (PPI) that denotes the number of pixels contained in one inch length of a display. For example, an Apple iPhone 4™ 's "Retina Display" with a 3.5" screen and 640x960 resolution has 326 PPI; an HD LCD with a 42" screen and 1920x1080 resolution has 54 PPI.

With higher PPI, the visual presentation looks smoother and is easier to read. By definition, small displays with high resolution have higher PPI, and consequently visual objects containing the same number of pixels appear smaller on them than what they appear on displays with the same physical size but lower resolution. Experimental results show that with the same PPI, a physically larger display improves task performance in 3D navigation [159].

Pixel Size

The reciprocal of PPI gives the *pixel size* in inches. For example, the pixel size of Apple iPhone 4™ is 1/326=0.003"(0.78mm) while that of an HD LCD is 1/54=0.018"(4.7mm).

Viewing Distance & Angle

Based on the information about the perceptual resolution of the human eye, we can calculate that an object is distinctly visible at a distance of less than or equal to 3438 times its size (i.e., $\tan(1/2$ arcminute)=0.000145 $\Longrightarrow$ Size of the object/2*Viewing Distance=0.000145 $\Longrightarrow$ 3438*Size of the object=Viewing Distance) [174]. Figure 2.6 shows the relationship between object size, viewing distance and visual angle.

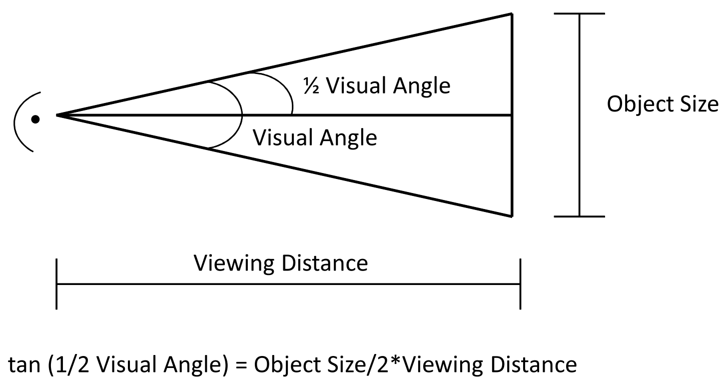


Figure 2.6: Object size, viewing distance and visual angle.

There is an optimal distance and angle to see a display as a whole. For example, mobile devices are usually held at a distance of 30–40cm and at a visual angle of 10°–12°, while the viewing distance and angle for a typical desktop computer are about 100cm and 25°–30° respectively. Table 2.1 shows display size, resolution, PPI, pixel size, viewing distance and viewing angle for different display devices.

Table 2.1: Display Characteristics: Size, Resolution, PPI, Pixel Size, Viewing Distance and Viewing Angle. All calculations are based on perceptual resolution of 20/20 human vision.

Device	**Size**	**Resolution**	**PPI**	**Pixel Size**	**Distance**	**Angle**
Nokia N900™	3.5"	800x480	267	0.95mm	32.7cm	10°
Apple iPhone4™	3.5"	640x960	326	0.78mm	27cm	11°
HTC Desire HD™	4.3"	480x800	240	1.06mm	36.4cm	9°
HTC Flyer™	7"	600x1024	169	1.50mm	51.7cm	11°
Apple iPad™	9.7"	786x1024	131	1.90mm	66.7cm	13°
Apple new iPad™	9.7"	2048x1536	264	0.96mm	33.08cm	25°
HDTV	42"	1920x1080	54	4.70mm	160cm	33°

2.5.8 Physical Navigation

Physical navigation refers to the physical movement of the foveal vision to look at different areas of the display; it may include eye saccades, head movements, reorientation of the torso, or walking towards/away from the display [12]. The smaller the display size, the less physical navigation is needed to view its contents and vice versa. For example, moving one's eyes or head away from a mobile display does not help one to view more information on the display as these movements will take visual attention away from the display. On the other hand, a large display provides a lot more space for physical navigation as one can move one's head or re-orient one's posture and still be able to view the information.

2.5.9 Virtual Navigation

Virtual navigation refers to the manipulation of the display (e.g., scrolling, panning, zooming) via input mechanisms (e.g., mouse, keyboard, touchscreen gestures) to bring information into view [12]. The smaller the display size, the more virtual navigation is required to view its contents and vice versa. For example, it requires a lot of panning and zooming to go through a large map on a handheld display. On the other hand, a large display can show more information at once and reduces the demand for virtual navigation.

2.5.10 Summary

Human foveal vision covers a very small region (i.e., 2°) of the visual field, hence, we make eye movements to look at the visual information outside the foveal region. The Useful Field Of View (UFOV) refers to the information one can extract at a glance. The nature of the viewing task, the type of visual information and the density of visual information influence the span of UFOV and the pattern of eye movements.

How much information a display can show at once depends on its size and resolution, and these characteristics determine the distance from and angle at which a display can be viewed as a whole. If the data is too large to fit into the visual field at once, humans adopt physical navigation. If the data is too large to fit into the display at once, users resort to virtual navigation.

2.6 Task Performance with Large Displays

It is an intuitive expectation that bigger displays provide better viewing experiences. Behavioural studies show human preference for larger objects in presentations [216]. This section provides an overview of research about task performance with different configurations comprising large displays.

Swaminathan and Sato [229] were among the first researchers to report on the qualitative benefits of using single versus multiple displays; they mainly used their multi-display prototype for group collaboration. Simmons [217] reported on users performing better in productivity tasks with the largest monitor that had slightly higher resolution, in comparison to those with smaller monitors. Czerwinski et al. [55] showed that participants using a multi-monitor configuration with increased resolution (3 monitors wide) performed better in complex, cognitively demanding productivity tasks (e.g., sensemaking) than on a single monitor.

A 4-month long diary study comparing the usage of a large (5mx2m) high-resolution (6144x2304 pixels) display with a single monitor and dual-monitor for information processing work [30] showed the participants' unanimous preference for using a large display. The stated reasons were that a large display facilitates multi-tasking and provides a more "immersive" experience. Sabri et al. [204] showed that a larger-sized display (made of 3x3 tiled monitors) affected the players' strategies and resulted in more wins and greater enjoyment for the players. Ball et al. [10] investigated the performance advantages of large high-resolution displays in visual search tasks with geo-spatial data. Moreover, they reported up to a ten-fold improvement in the performance time with larger displays when the participants used physical navigation rather than virtual navigation [13].

The performance improvement with large displays is task-dependent; no performance advantages with a large display have been shown in reading comprehension tasks [232] but spatial tasks benefit from the wider visual field offered by a large display [231, 232]. Studies report on improved task performance with large displays in spatial and virtual path selection [232, 233], 3D navigation [56], and 2D navigation and visualization [10, 272] tasks.

Ball et al. [12] attribute the advantages of large displays to three main factors:

- *Peripheral Vision.* Small displays emphasise foveal vision and provide minimal opportunities to harness peripheral vision. Large high-resolution displays provide a greater peripheral area, and help smooth shifting of the foveal vision across the visual field.
- *Physical Navigation.* The increased physical navigation with large displays, and subsequently less virtual navigation, can result in better performance.
- *Embodied Interaction.* The theory of embodied interaction [63] suggests that the

cognitive mind is inseparable from the physical body and the combination of mental and physical resources—that includes peripheral vision and physical navigation—produce an impact. Experimental evidence confirms the combined role of peripheral vision and physical navigation in improving task performance with large displays [12].

2.7 Navigation Patterns with Displays

The *navigation pattern* refers to the human interactions with the display device in order to view the information that lies outside the focal vision. A display supports different navigation patterns to different extents depending on its specifications such as form factor, physical size, distance from observer, and manipulation of the screen's viewport (e.g. via scrolling, swiping).

As discussed earlier, physical navigation (see Section 2.5.8) involves movement of the body around the display to bring information into one's viewpoint while virtual navigation (see Section 2.5.9) involves manipulating the display to bring information into the screen's view port. Physical navigation can be classified into *egocentric* and *exocentric*, usually depending on the physical size of the display as well as its distance from the observer.

2.7.1 Egocentric

Egocentric navigation involves moving one's body towards/away from the display. It may include moving one's eyes/head, rotating the torso, or walking up to or away from the display. Large situated displays allow for high levels of egocentric navigation, while the levels of this are low with small-sized displays (e.g., smartphones, laptops).

2.7.2 Exocentric

Exocentric navigation involves moving a display close to or away from one's body. Portable displays can allow for high levels of exocentric navigation, while levels of this are medium in desktop monitors, and low in large displays.

2.7.3 Virtual

When the information does not fit within the display at once, it requires *virtual navigation* to bring it into the viewpoint [12]. Virtual navigation may include panning, zooming, or adjusting the resolution of the display. Virtual navigation is supported by multi-window and virtual desktop features in most operating systems for computers (e.g., Windows, OS X, Linux) and by the screen-swiping feature on many smartphone platforms (e.g., iOS, Android). By default, most display devices can accommodate a high level of virtual navigation, although the application and interface developers may restrict the level of accommodation.

2.7.4 Summary of Navigation Patterns

According to their physical size, distance from the observer and available provisions for adjusting their viewpoints, different displays can offer opportunities for exocentric, egocentric and virtual navigation along a spectrum. Table 2.2 shows the provision of different navigation patterns in some of the work containing MDUIs.

2.7.5 Attention Switching & Navigation Patterns

In cognitive psychology, *attention* is defined as the process of selectively focusing on one thing while ignoring the rest. It has also been referred to as the "allocation of processing resources" [5]. Attention involves responding to various stimuli that can be visual, auditory

Table 2.2: Navigation Patterns in Multi-Display User Interfaces.

MDUIs	**Egocentric**	**Exocentric**	**Virtual**
Multi-monitor desktop	Medium	Low	High
Nintendo DS	Low	High	High
Bumping [96]	Medium	Medium	High
Geney^{TM} [57]	Low	High	High
Courtyard [237]	High	Low	High
UbiTable [214]	Medium	Medium	High
SharedNotes [82]	Medium	High	High
Projector Phones	Low	High	High
SildeShow Commander [150]	Medium	Medium	High
i-LAND [225]	High	Low	High

or tactile. Extensive research on attention has been reported in the areas of psychology and neuro-science [5, 267].

A comprehensive analysis of different modalities of attention is beyond the scope of this work. For the purposes of this thesis, we restrict our exploration to the switching of visual attention across different user interface elements that are visually separated across different displays in a multi-display environment. Moreover, this work is particularly focused on cross-display attention switching in mobile interaction with large displays.

Considering the navigation patterns described in Section 2.7, the focus of this thesis is on visual attention switching between a handheld mobile device and a vertical large display, following the egocentric navigation pattern. In egocentric navigation, attention switching occurs along a continuum and we are particularly concerned with that due to eye and head movements, as depicted in Figure 2.7.

An exhaustive exploration of visual attention-switching patterns exhibited in interaction between adjacent vertical displays, as well as those within a large display are also beyond the scope of the current work.

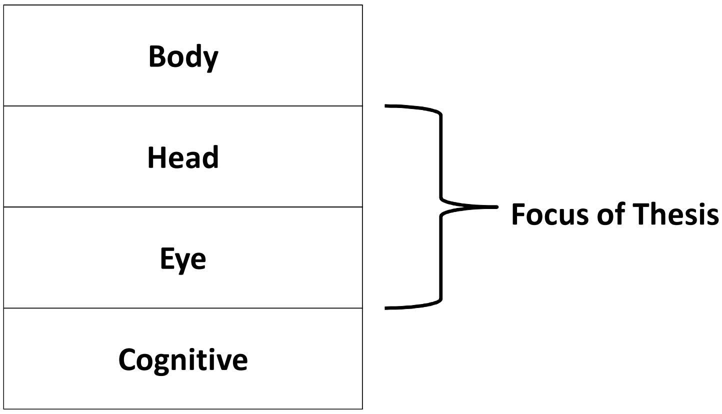


Figure 2.7: Continuum of Attention Switching in Egocentric Navigation.

2.8 Summary and Discussion

In this chapter, we discuss the proliferation of computing devices of various form factors and report on studies about multi-device usage. We provide an overview of computing paradigms that envisage the phenomenon of integrated user experience across heterogeneous devices. After this, we highlight some approaches towards the design of user interfaces for multi-display systems. We discuss some aspects of human vision and perception, as well as characteristics of display devices, that can be relevant to the design of effective multi-display user interfaces (MDUIs). We explain the performance gains of large displays and relate them to the use of peripheral vision, physical navigation and embodied interaction. We indicate navigation patterns supported by different displays and highlight the scope of thesis with respect to the attention switching associated with the continuum of the navigation pattern being investigated.

It is expected that forthcoming MDUIs will support hybrid forms of navigation patterns, such as the zoom level of smartphones adjusting itself as the user moves it towards or away from the eye, hence resulting in a hybrid pattern of exocentric and virtual navigation. Moreover, Attentive User Interfaces [136], interfaces that change their behaviour by paying attention to the user's activities, can support a hybrid pattern of egocentric and virtual navigation. The patterns of visual attention switching, and their effects on task performance with MDUIs based on those technologies, is an interesting area to be explored in the future.

Discovery consists of seeing what everybody has seen and thinking what nobody has thought.

Albert Szent-Gyorgyi

Chapter 3

A Taxonomy Based on Visual Arrangement of Multi-Display User Interfaces *

As discussed previously in Chapter 2, Multi-display User Interfaces (MDUIs) have the potential to improve interaction because combining heterogeneous display devices allows people to use the right display for the right subtask. For example, they can take advantage of the mobility and direct touch of tablets and PDAs, while simultaneously being able to see their data on a very large display without the limitations of mobile screens [179]. Efforts are already under way to support the design and implementation of user interface (UI) elements distributed across multiple devices [19, 133].

Although MDUIs allow flexibility for the design of novel interfaces with optimal input, output and collaborative capabilities, they also introduce the overhead due to visual attention shifts. Because human vision can only focus on a limited area at a glance [220], distributing UI elements across multiple displays will inevitably cause switching of visual attention

*Some of the contributions presented in this chapter have also appeared in [182]. Miguel Nacenta assisted the first author in identifying some factors in the taxonomy, and Aaron Quigley provided valuable feedback on the taxonomy and helped refining it.

that might involve cognitive focus, gaze, head or body displacement. The overall effects of such visual attention switching will probably depend on the task (e.g., [183, 230]), as well as the design of input and output aspects of the system. Unfortunately, making informed decisions regarding MDUI design is difficult because the existing literature is partial and fragmented, and there is no clear identification of factors that can influence switching of visual attention in different visual arrangements of MDUIs. In an attempt to fill this gap, we undertook a literature survey of existing taxonomies that are applicable to MDUIs. In this chapter, we identify a set of factors associated with the visual arrangement of UI elements that can affect attention switching, present a taxonomy of the work containing MDUIs based on those factors, and review existing research that is relevant to each factor.

This chapter starts by providing a critical overview of the existing taxonomies that are applicable to MDUIs, in Section 3.1. The factors that constitute our taxonomy are presented sequentially in Section 3.2. For each factor, we describe different categories, classify existing systems according to each category of the factor, and discuss its relevance to cross-display switching. We highlight the scope of this thesis with respect to our taxonomy of MDUIs in Section 3.3 before concluding the chapter.

3.1 Taxonomies for MDUIs

The research area of multi-display environments has been very active in the last few years; several researchers have proposed taxonomies or categorisations that, although generally having different purposes, provide a valuable start point for our work. In this section, we discuss some classifications in the existing literature that are applicable to the systems containing MDUIs.

3.1.1 Configuration of Multiple Displays

Swaminathan and Sato [229] indicate three configurations of multiple displays, as given below.

- *Distant-contiguous* configurations consist of multiple displays placed at a large distance from the user, such that they occupy the same visual angle as a standard desktop monitor.
- *Desktop-contiguous* configurations consist of multiple displays placed at a distance equivalent to a standard desktop monitor, drastically widening the available visual angle.
- *Non-contiguous* configurations consist of display surfaces at different distances from the user and that do not occupy a contiguous physical display space.

We borrow this classification to formulate categories according to the *display contiguity* factor in our taxonomy as explained in Section 3.2.1.

3.1.2 Taxonomy for Mobile Interaction

Ballagas et al. [15] propose a taxonomy for mobile interaction with situated displays, that is based on the taxonomy of desktop-GUI proposed by Foley et al. [74]. Ballagas et al. borrow three sub-tasks from desktop-GUI taxonomy that are relevant to mobile input space, as given below.

- *Position* (specifying a position in application coordinates).
- *Orient* (specifying an orientation in a coordinate system).
- *Select* (making a selection from a set of alternatives).

In order to accommodate the increased diversity of mobile input, they included four additional factors in their taxonomy, as given below.

- *Dimensionality* (up to 3 dimensions).
- *Environmental feedback* (continuous or discrete).
- *Measurement* (relative or absolute).
- *Interaction style* (direct or indirect).

The "interaction style" factor of this taxonomy is the most relevant for visual attention switching and it corresponds to the *input directness* factor in our taxonomy, and will be discussed further in Section 3.2.4.

3.1.3 Taxonomy for Private Mobile Devices and Public Situated Displays

Dix and Sas [62] outline a taxonomy of coupling of private mobile devices and public situated displays based on six factors, as given below.

- *Physical size* (poppyseed-scale, inch-scale, foot-scale, yard-scale, perch*-scale).
- *Input device use* (selection/pointing, text input, storage, user ID, display ID, content ID, sensing, interaction/display surface).
- *Social context* (witting/unwitting participants and/or witting/unwitting bystanders).
- *Participant-audience conflicts* (conflicts of content, conflicts of pace).
- *Spatial context* (fully public, semi-public, semi-private).

*A perch equals 5.5 yards.

- *Multiple device interaction* (when and where interactions with multiple devices happen).

A comprehensive analysis of the aforementioned taxonomy is beyond the scope of this thesis. The factor "multiple device interaction" is relevant for our purpose because it affects how content is related across different displays, which corresponds to the *content coordination* factor in our taxonomy as explained in Section 3.2.3.

3.1.4 Taxonomy of Multi-person-display Ecosystems

Terrenghi et al. [239] present a taxonomy of multi-person interactions in multi-display ecosystems that identifies three main factors which constitute what they call the "geometries of interaction". These factors are given below.

- *Size of ecosystem* (inch-scale, foot-scale, yard-scale, perch-scale, chain*-scale).
- *Nature of social interaction* (one-one, one-few, few-few, one/few-many, many-many).
- *Interaction methods for binding multiple displays* (synchronous co-located human movement, continuous action, actions and infrastructure).

The key factor in this taxonomy is the "size of ecosystem" as it implicitly determines if the displays containing MDUIs lie within or exceed the human visual field, and consequently influences attention switching. This factor corresponds to the *angular coverage* factor in our taxonomy and will be discussed further in Section 3.2.2.

The "nature of social interaction" is not relevant here as this work is focused on single-user tasks in a multi-display environment. Moreover, "interaction methods for binding multiple displays" are also not applicable because the experiments assume (and make use of) a pre-configured network connection between the mobile device and the large display.

*A chain equals 22 yards.

3.1.5 Taxonomy of Cross-Display Object Movement Techniques

Nacenta et al. [153] introduce a taxonomy that classifies interaction techniques for moving visual objects across different displays within three dimensions as follows:

- *Referential domain*. This signifies the way the user and the system refer to a particular display. Depending on the referential domain, an interaction technique can be *spatial* ("display on the left side of the source display") or *non-spatial* ("display A").
- *Display Configuration*. This refers to the way displays are arranged in the logical workspace. Based on display configuration, an interaction technique can be *planar* (showing results of object movement as if all displays lie in the same plane), *perspective* (showing results of object movement as if all displays lie within the user's perspective) or *literal* (shows results based on the physical contact between displays).
- *Control paradigm*. Three control possibilities exist for cross-display interaction techniques: *open loop* (provides a feedback channel when the object is in its final position), *closed loop* (allows the user to adjust the execution of the action before it is finished) and *intermittent open/closed control* (techniques that account for the "displayless space" between displays).

Of these, only "display configuration" is directly relevant for attention switching and relates to the *display contiguity* factor in our taxonomy as explained in Section 3.2.1.

3.1.6 Model of Distributed Interaction Space

By contrast, Luyten and Coninx [133] propose a model of Distributed Interaction Space (DIS) with an implicit taxonomy. A Distributed Interaction Space (DIS) consists of user interface (UI) elements distributed across input/output resources of multiple computing devices [133]. The behaviour and performance of a DIS user is not only affected by the UI components but also by the characteristics of the computing devices (e.g., mobility, tangibility) containing these UI components. Some empirical studies look at how the distribution of UI elements across different devices affect task performance [44].

A DIS has been described as having three dimensions [133] as follows:

- *Location-oriented* (location of UI elements in the user's space).
- *Task-oriented* (tasks one or more users execute to achieve a shared goal).
- *Device-oriented* (interaction resources which represent the separate input/output capabilities of each device)

In this thesis, our focus is on "device-oriented" DIS because it deals with the input and output capabilities of the devices containing MDUIs.

3.2 Taxonomy Based on Visual Arrangement of Multi-Display User Interfaces (MDUIs)

Building upon the taxonomies described in Section 3.1, we propose a taxonomy to help understand the relationship between MDUIs configuration and cross-display switching. The factors in our taxonomy represent the characteristics associated with the visual arrangement of MDUIs that can affect attention-switching patterns. As emphasised beforehand, this research investigates the performance effects of cross-display switching in MDUIs and any attention switching due to auditory or haptic stimuli is excluded from the current discussion. Moreover, it is also assumed that no external distractions exist in the environment and the visual attention is distributed only across UI elements in a multi-display environment.

The factors in our taxonomy are as follows:

- *Display Contiguity* (visual field contiguity, depth contiguity) Section 3.2.1.

- *Angular Coverage* (panorama, field-wide, fovea-wide) Section 3.2.2.
- *Content Coordination* (cloned, extended, coordinated) Section 3.2.3.
- *Input Directness* (direct, indirect, hybrid) Section 3.2.4.
- *Input-Display Correspondence* (global, redirectional, local) Section 3.2.5.

For each factor, the following sub-sections provide a detailed explanation, classify some of the existing work containing MDUIs accordingly, and analyse the relevance to cross-display switching.

3.2.1 Display Contiguity

Swaminathan and Sato's classification of multi-display configurations [229] helps to explain the spatial relationship between desktop displays; however, it does not take into account the increasing diversity of display form factors, such as handheld displays. For our purposes, we define two categories of display contiguity: visual field contiguity and depth contiguity.

- *Visual Field Contiguity*. Displays appear to be contiguous in the visual field, but may be separated by bezels or placed at different distances from the observer.
- *Depth Contiguity*. Displays are placed at the same distance from the observer but they may not be placed adjacent to each other.

This classification generates four different permutations of display contiguity (see Figure 3.1). We classify some of the existing work containing MDUIs under each of those permutations.

Visual Field & Depth Contiguous

Displays in this category are placed at the same distance from the observer and they also appear contiguous in the visual field, as shown in Figure 3.1a. Multi-monitor arrangements

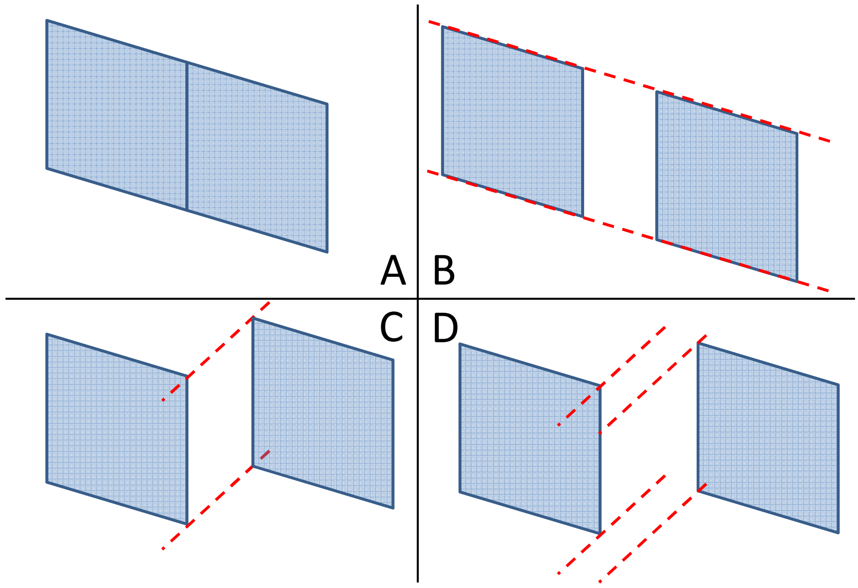


Figure 3.1: Display Contiguity: A) visual field & depth contiguous, B) visual field discontiguous & depth contiguous (C) visual field contiguous & depth discontiguous (D) visual field & depth discontiguous.

are often arranged in this configuration. Another examples are ConnecTable displays [236] that form a larger display area when put together, or display walls composed of multiple flat displays. Junkyard Jumbotron [117] allows the combination of multiple mobile devices into one large virtual display. Siftables [144] are cookie-sized computing devices that form a single interface when placed together as shown in Figure 3.2.

Dynamo [109] is an interactive wall display that is composed of one or more displays that can be tiled both horizontally and vertically. Its dual-projected, vertically tiled arrangement exhibits contiguity in visual field & depth, and is shown in Figure 3.3.

Wall displays per se in i-LAND [225] and iRoom [111] (shown in Figure 3.4) projects also exhibit contiguity in visual field & depth. However, spreading the display space across

Figure 3.2: Visual Field & Depth Contiguous: Siftables (used with permission from [144]).

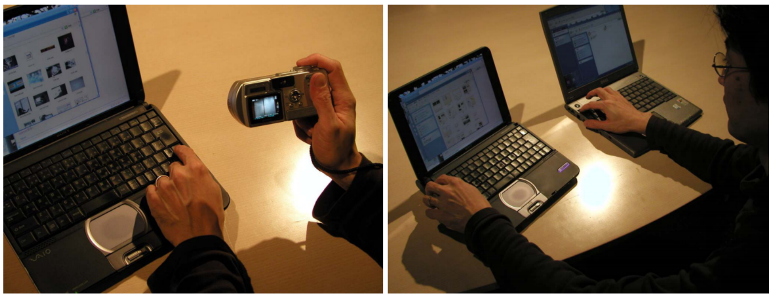
Figure 3.3: Visual Field & Depth Contiguous: Dual-projected vertically tiled arrangement in Dynamo (used with permission from [109]).

tabletop surfaces changes the contiguity in both the visual field and the depth.

Figure 3.4: iRoom: Three touch-sensitive wall displays, a pen-touch Interactive Mural and a table display (used with permission from [111]).

Visual Field Discontiguous & Depth Contiguous

Here displays appear discontiguous in the visual field but they are placed at the same distance from the observer, as shown in Figure 3.1b. For example, in Synctap [192], tablets are typically separate from each other but in the same plane as shown in Figure 3.5b. In the Geney^{TM} [57] collaborative system, PDAs are visually non-contiguous, but they are usually placed at the same depth.



(a) (b)

Figure 3.5: Visual Field Discontiguous & Depth Contiguous: SyncTap operations between: (a) a digital camera and a laptop, (b) two laptops (used with permission from [192]).

Visual Field Contiguous & Depth Non-contiguous

Displays in this category are placed at different distances from the observer but they appear contiguous in the visual field, as shown in Figure 3.1c. For example, in E-conic [156] (see Figure 3.6), displays are placed at different depths but they can appear to be in the same visual field, depending on the user's perspective.

Figure 3.6: Visual Field Contiguous & Depth Non-contiguous: Econic perspective-aware UI (used with permission from [156]).

In Ubiquitous Graphics [207] (see Figure 3.7), a mobile device is held in front of the stationary display to view additional information about the contents shown on the latter. Both mobile and large displays appear to overlap in the same visual field but are positioned at different depths.

The SlideShow Commander program [151] enables a PDA to show a thumbnail picture of a presentation slide running on a computer; notes for the slide, the list of slides, and other information are also shown on the PDA. Both the PDA and the computer appear contiguous in the same visual field while being at different depths.

Figure 3.7: Visual Field Contiguous & Depth Non-contiguous: In Ubiquitous Graphics, a user holds up a tablet PC in front of a large projected image to view details (used with permission from [207]).

Visual Field & Depth Discontiguous

Displays here are placed at different distances from the observer and they do not appear contiguous in the visual field, as shown in Figure 3.1d. For example, in Courtyard [237], a shared overview is shown on a large screen and per-user details are presented on individual screens. In SharedNotes [82], each handheld PDA shows the personal contents while the public contents are shown on the large wall display. In the iPad Scrabble game, the iPad serves as a Scrabble board and the tiles are arranged on iPhones so other players can't see them [211].

Systems that integrate wall displays with tabletop surfaces also fall into this category. For example, in Dynamo, a vertically tiled wall and tabletop configuration (see Figure 3.8) exhibits discontiguity in visual field & depth. The same holds true for the configuration of wall displays and tabletop surfaces in i-LAND [225] and iRoom [111].

Some other examples include the Augmented Surfaces project [193] that supports integration of laptop, table and wall displays to allow smooth exchange of digital contents across these displays, and WeSpace [260] that integrates a large wall display with a multi-touch table (see Figure 3.9).

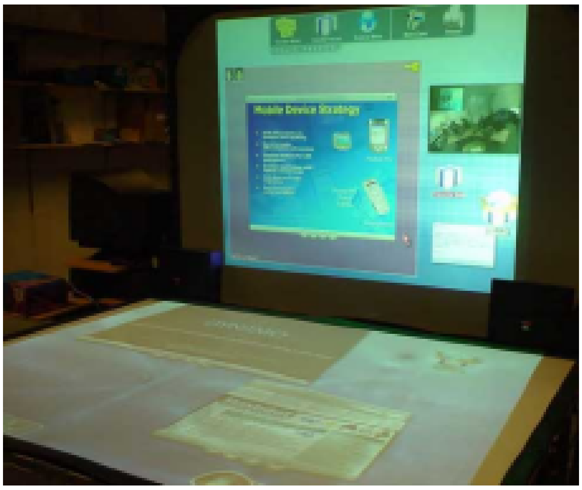


Figure 3.8: Visual Field & Depth Discontiguous: wall and tabletop display in Dynamo (used with permission from [109]).

Figure 3.9: WeSpace: Large data wall with a multi-user multi-touch tabletop (used with permission from [260]).

Summary of Existing Systems

Table 3.1 shows the contiguity of displays in some of the work containing MDUIs. It is noteworthy that some MDUIs can fall into multiple categories if the position of the user or displays is adaptable. For example, in regular use, Geney™ [57] supports "visual field discontiguity & depth contiguity" when the handheld displays are held close but it can switch to "visual field & depth discontiguity" if those displays are held farther away.

Table 3.1: Display Contiguity in Multi-Display User Interfaces.

	V.F. Contiguous	**V.F. Discontiguous**
Depth Contiguous	Multi-monitor desktop, Multi-tablet composition [134], Connectable [236], Stitched tablets [97], Bumped tablets [96], Junkyard Jumbotron [117], Siftables [144], Dynamo wall displays [109], iRoom wall displays [111], i-LAND wall displays [225]	Geney^{TM} [57], Synctap [192]
Depth Discontiguous	E-conic [156], Magic Lense [201], Touch Projector [34], Ubiquitous Graphics [207]	Courtyard [237], Dynamo wall displays and tabletop [109], i-LAND wall displays and tabletop, [225], Interactive TV Remote [199], iRoom wall displays and tabletop [111], iPad Scrabble [211], Projector Phone [91], SharedNotes [82], UbiTable [214], WeSpace [260], Wincuts [234]

Relevance to Cross-Display Switching

In multi-display environments, visual separation between displays can occur due to the bezels between two adjacent displays or the physical gap between non-contiguous displays placed at different depths and distances from the observer. For example, in an office environment containing displays such as laptops, desktop computers and wall displays, there exist numerous inter-display visual separations. Nacenta et al. [154] refer to the physical discontinuity between multiple displays as *displayless space*.

The category of display contiguity can persuade viewers to adopt different levels of attention switching with MDUIs that can affect performance in various tasks. Tan and Czerwinski [230] found no effects of visual separation due to bezels or inter-screen physical distance alone, for text comparison and proofreading tasks. However, bezel and depth together caused a detrimental though negligible effect on performance in the aforementioned tasks [230]. Yang et al. [270] found that it was the relative depth, and not bezels, between Lens-Mouse (a mouse with a screen on top) and the computer screen that caused degradation of task performance. Bi et al. [29] found the bezels on tiled-monitor large displays to be detrimental to the performance in straight-tunnel steering task but not in visual search and target selection tasks. Nacenta et al. [154] showed that the "displayless space" (i.e., physical gap between displays) slows down the movement of visual objects across displays. Cauchard et al. [39] found that in a mobile multi-display environment, although performance in a visual search task was unaffected by the displays being in the same or in different visual fields, the number of gaze switches was higher when both displays were in the same visual field. In contrast, our study [183] (further explained in Chapter 5) suggests significant degradation of performance due to replicating contents across a mobile handheld display and a vertical large display in visual search tasks.

Although not identical in scope, the research on multi-view visualizations is also helpful in understanding cognitive processes involved with the use of multiple-views [228]. A study in dual-view visualizations demonstrated that the time cost for context switching may not be significant [50].

The aforementioned examples from the existing literature suggest that performance effects of display contiguity differ with respect to the task at hand. Bezels per se have not been shown to cause any degradation in performance [29, 230, 270] except in the straight-tunnel steering task [29] with tiled-monitor displays. Apparently, the performance cost in the straight-tunnel steering task is due to the discontinuity in visual representation induced by the bezels, rather than attention switching. However, bezels combined with the physical gap (i.e., "displayless space") between displays impede performance in cross-display object movement [154]. That is why we excluded bezels from consideration for the systems that are contiguous in the visual field.

On the other hand, relative depth between displays is reported to have caused an overhead in some tasks across multiple displays [183, 226, 270]. A study reveals that people have difficulty in disengaging attention from objects near their hands [2]. Users are reported to be faster at target selection between two displays placed side-by-side compared to doing the same task on the same displays positioned with a slight gap (45mm) in-between [137]. In a study about reading text on a mobile device and a large screen, it was noticed that moving their heads up and down between the screens placed at different depths led the users to perceive them as separate devices, rather than as two screens attached to the same system [80].

In contrast to that, Grudin [85] suggested that the division of space afforded by multiple non-contiguous displays is sometimes more beneficial than having a single contiguous display space. He observed that the visible gap between individual monitors discouraged users from having windows span multiple displays, and they instead used additional monitors to separate windows belonging to different tasks. Users typically divided primary and peripheral tasks between different monitors.

Further research is needed to determine how display contiguities in visual field or depth contribute to attention switching and performance differences in various tasks across MDUIs.

3.2.2 Angular Coverage

Another important factor that might influence the need for visual attention shifts is the angular size covered by the MDUIs. This factor is inspired by the *size of ecosystem* described in the taxonomy proposed by Terrenghi et al. [239] and *physical size* in the taxonomy proposed by Dix and Sas [62]. We adapt physical size to angular coverage in order to consider the relationship between the point of view of the user with respect to the size of the MDUIs.

This factor is more continuous in nature than the other factors in our taxonomy. Nevertheless, we define three marker points in this continuum: panorama, field-wide and fovea-wide.

Panorama

These are systems that surround the user, and therefore require the movement of head or body to view the whole display space. This does not mean that a single display must cover the whole area, rather that the displays that comprise the system are situated in such a way that they cover a large part of the spherical area around the head of the observer. For example, any room that has displays facing one another will be panoramic to a user located between them. Most room-based MDUIs will therefore fall close to this end of the continuum (e.g., E-conic [156], i-LAND [225], Ubi-Cursor [269]).

Field-wide

The human visual field typically covers around 200° horizontally and 135° vertically [256]. Field-wide systems have displays whose angular coverage fits within these parameters and can therefore be centred in the fovea by changing the direction of gaze. Systems that are closer to field-wide than fovea-wide include MDUIs with wall-based large displays (e.g., Dynamo [109], u-Texture [125], UbiTable [214]).

Fovea-wide

At the other end of the continuum, we place systems where the whole display space fits within a human fovea (about 2°). There are few MDUIs that exist at this extreme end of the continuum, but some examples are closer to the fovea-wide than to the field-wide category (e.g., Siftables [144], Geney™ [57]).

Summary of Existing Systems

Some of the systems containing MDUIs are categorised by their angular coverage in Figure 3.10. As stated earlier, these are subject to the user and display repositioning.

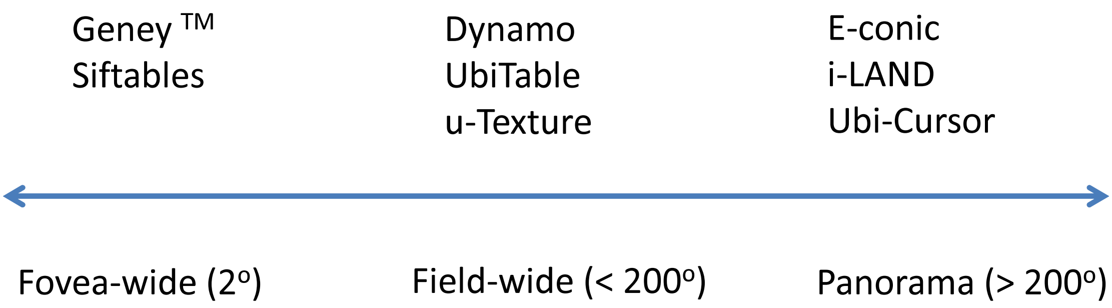


Figure 3.10: Angular Coverage in Multi-Display User Interfaces.

Relevance to Cross-Display Switching

Terrenghi et al. [239] associate the size of an ecosystem with eye-, head-, and body movement, which is directly relevant to the focus of our taxonomy. It is expected that MDUIs that have wider angular coverage will require more attention switching and that may lead to greater overheads in terms of performance. This area has not been studied in the context of MDUIs, although we can speculate that some degradation in performance (e.g., [269]) is due to this effect. This issue needs to be explored further.

3.2.3 Content Coordination

Content coordination refers to how the contents in different displays are semantically connected. This notion is motivated by the visualization research [198, 249] in *Coordinated & Multiple Views* (CMVs) i.e., the views that contain different visualizations of the same data. Below, we specify three categories of content coordination.

Cloned

In this category, all displays mirror each other's content, although each display might be of a different size and resolution. This type of coordination is supported by most operating systems, and it is common in projector-connected laptops, projector phones and on some commercial systems such as Apple's Airplay™ technology [3]. The HTC Desire HD™

Android handset allows users to stream photos, music, and video to DLNA-enabled devices (e.g., a networked media server or a standard TV) with a wireless adapter. The Nokia N8™ handset can stream media files to a High Definition Television (HDTV) via its High-Definition Multimedia Interface (HDMI) port. Virtual Network Computing (VNC) [196] allows the screen of a remote computer to be replicated and manipulated on a local computer as on the remote screen. X11 [268] and Windows Remote Desktop Services (RDS) [263] also enable cloning of the interface across standard personal computers.

Extended

In this category, multiple displays act together as a large extended display that spans those individual displays. The different displays show different parts of the same visual whole. This type of coordination is common with multiple monitors connected to the same desktop computer. Lyons et al. [134] built a multi-display composition system that enables several tablet computers to join together over a wireless network to form a larger logical display. Hinckley et al. [96] enabled two tablets to form a large extended display when they are bumped together.

This type of content coordination is supported by IBM's Deep Computing Visualization (DCV) [107] middleware that allows users to view the same three-dimensional (3D) OpenGL applications spread across multiple screens. Chromium [47] also enables the rendering of graphics on a cluster of workstations, all of which behave like one extended screen.

Coordinated

In this category, each display shows a different content, but the contents are related in some way other than complete replication (i.e., other than cloned). There are many ways to coordinate the content across displays; for example, one display can show an augmented or a partial view of a certain area of the other (e.g., [34, 57, 82, 183, 201, 207]), or one display can serve as a remote control for the other (e.g., [19, 199, 211]).

Summary of Existing Systems

Table 3.2 shows the coordination of content in some of the work containing MDUIs. In some cases, it is the application or the usage that determines the type of content coordination, and some systems can support applications that are categorised differently.

Table 3.2: Content Coordination in Multi-Display User Interfaces.

Content Coordination	Examples
Cloned	Projector Phone [91], Projector with laptop, VNC-enable devices [196]
Extended	Connectables [236], E-conic [156], Multi-monitor desktop, Dual-screen phone, Bumped tablets [96], Junkyard Jumbotron [117], Multi-Display Composition [134], Stitched tablets [97]
Coordinated	UbiTable [214], SharedNotes [82], Augmented Surfaces [193], i-LAND [225], iPad Scrabble [211], Magic Lens [201], Interactive TV Remote [199], Touch projector[34], Impromptu [31], Ubiquitous Graphics [207], Remote annotation to DynaWall in iRoom [111], Geney™ [57], Courtyard [237]

Relevance to Cross-Display Switching

Although it seems likely that content coordination between UI elements in different displays will affect attention switching behaviour, there are, to our knowledge, no studies that explicitly investigate this phenomenon. Some of the previous work partially addresses this issue. For example, design guidelines for *Coordinated & Multiple Views* suggest that views should highlight different aspects of the same information; otherwise context switching between the different views can undermine user interaction [249]. This suggests evading *cloned* arrangements for tasks involving a single user.

Our user study [183] (further explained in Chapter 5) found that simple *coordinated* visuals on a mobile-large display MDUI can cause attention switches linked to the performance overhead for text, image and map search tasks. Forlines et al. [76] showed that for an individual user, an image shown in different rotations (i.e., coordinated arrangement) on four vertical displays screens degraded performance in a visual search task, compared to the same image shown on a single vertical display. Bi et al. [29] showed that splitting an object across screens (i.e., extended arrangement) leads to increased completion times in the straight-tunnel steering task and causes more errors in a visual search task. Grudin [85] observed that a visible gap between individual monitors discouraged users from making the content span multiple displays, and that they instead used additional monitors to separate content belonging to different tasks (i.e., extended arrangement). Further research is needed to investigate the influence of different categories of content coordination on attention switching and task performance.

3.2.4 Input Directness

The previous factors discussed mostly deal with the spatial distribution of visual elements across displays; however, how input is provided in MDUIs can also play a role since visual attention is often involved in the input loop. The following categories correspond to traditional HCI categorisations of input.

Direct

Input is *direct* when the motor actions of the user take place roughly in the same location as the output (e.g., in most touch interfaces). From the user's perspective, no intercession between input and output is noticeable.

Indirect

Input is *indirect* when there is a spatial separation between the input device (where the user's motor actions occur) and where the visual feedback is provided (e.g., using a mouse to control an on-screen cursor).

Hybrid

We classify the input of an MDUI as *hybrid* when direct input is present but alternative feedback is provided in a different display, which allows the user to switch to indirect input if desired. Hybrid input is common in systems where output is *cloned* and the main input device is *direct*. Examples include projector phones as well as systems with any kind of World-In-Miniature (WIM) input mechanisms [224] where the input to the miniaturised view is reflected as output in both the miniaturised and the full-scale views.

The directness of input in relation to the location of output has been discussed earlier for single-display systems (e.g., [155]). Although not identical, this phenomenon is also applicable to MDUIs.

Summary of Existing Systems

Table 3.3 shows the directness of input in some of the existing work containing MDUIs.

Table 3.3: Directness of Input in Multi-Display User Interfaces.

Directness of Input	**Examples**
Direct	Bumped tablets [96], Junkyard Jumbotron [117], Pick and Drop [190], Geney^{TM} [57], Stitched tablets [97], i-LAND [225], Connectables [236], SyncTap [192]
Indirect	ProjectorPhone [91], Remote annotation to DynaWall in iRoom [111], E-conic [156], Multi-monitor desktop, Courtyard [237]
Hybrid	SharedNotes [82], LensMouse [270], Projector Phone, Ubiquitous Graphics [207], Touch Projector [34], UbiTable [214], WIM [224]

Relevance to Cross-Display Switching

McLaughlin et al. [141] highlighted that the input device itself imposes attentional demands and that a user's task performance is affected by the match between the input device and the action performed on the interface. Indirect input is good for tasks such as repetitive motion and precise movement, while direct input is good for pointing tasks and ballistic movements [141].

We have not encountered any research that explicitly compares attention switching and the performance effects related to input directness in MDUIs. However, some efforts in related domains report results that might be applicable to MDUIs. Nacenta et al. [155] explored the relative performance of differing input directness in tabletop interactions. Forlines et al. [77] found better performance with direct input for bimanual tasks, and equivalent performance with direct and indirect input for unimanual tasks on a tabletop display. Further research is needed to explore the role of input directness in attention switching and performance in different tasks across MDUIs. In particular, it is important to know whether hybrid input configurations result in equivalent or degraded performances due to the possibility of switching input directness between and within tasks, which would likely require visual attention switches.

3.2.5 Input-Display Correspondence

This factor is closely coupled to the input directness factor and partially determines it. We distinguish three types of input-display correspondence.

Global

In this kind of system, input control is common for all the displays and is bound to none of them in particular. For example, the standard multi-monitor arrangement uses a single mouse and keyboard to control all sources of output. Similarly in E-conic [156], any user with an air mouse can operate any of the displays. By definition, MDUIs relying on global input also have indirect input.

Redirectional

This category describes systems where the input mechanism is provided on a single display and input is redirected to other displays to manipulate content on their surfaces. An example is the Point & Shoot technique [14], where the camera phone provides an input mechanism to interact with the large display. Typical projector-connected devices also fall into this category where the input is provided on the display device to manipulate the projected output. Robertson et al.'s PDA controlled interactive real estate information system [199] also falls within this category. Other examples include the use of mobile phones as optical mice [14], magic lenses [201] or as conduits for exchanging content between displays [34]. Berger et al. [27] built a solution that allows users to transfer their e-mail messages from a mobile phone to an external large display. Redirectional input-display correspondence will typically result in hybrid input directness.

Local

Local input-display correspondence refers to systems where each display is provided with its own input mechanism. For example, each PDA in Geney™ [57] has an independent input. The same holds true for the displays supporting Pick-and-drop technique [189]. The SyncTap [192] system establishes a network connection between two devices when the user synchronously presses and releases the button on each device. The SharedNotes system allows data sharing between PDAs and shared public screens in a similar fashion [82]. Hosio et al. [101] present a platform to support distributed user interfaces on interactive large displays and mobile devices; an input mechanism is provided on both the mobile device and the large display. Usually, local input-display correspondence takes advantage of direct input.

Summary of Existing Systems

Table 3.4 shows the input-display correspondence in some of the existing work containing MDUIs.

Table 3.4: Input-Display Correspondence in Multi-Display User Interfaces.

Input-Display Correspondence	**Examples**
Global	Multi-monitor desktop, Dual-screen phone, Dynamo [109]
Redirectional	Projector Phone [91], Media-player Remote [218], Mobi-Toss [209], Interactive TV Remote [40, 68, 199], Touch Projector [34], Ubiquitous Graphics [207]
Local	UbiTable[214], SharedNotes [82], SlideShow Commander [150], i-LAND [225], Geney^{TM} [57], Courtyard [237], Bumped tablets [96], Connectables [236], Stitched tablets [97], SyncTap [192], iPad Scrabble [211]

Relevance to Cross-Display Switching

Our eyes can move very quickly compared to our hands and limbs [274]. Users typically focus on the target first, before actuating input control [110, 252]. This implies that the correspondence between the input and the display can also affect switching of visual attention across multiple displays.

The effects on visual attention switching of input-display correspondence are partly determined by the close relationship of the latter with input directness. However, there are some additional considerations. Since MDUIs with separate displays and redirectional input-display correspondence tend to use mobile devices for input, it is likely that the spatial mapping between the input space (in the mobile device) and the output space (in a separate device) is not straightforward. Several studies have shown that this kind of mapping is detrimental to task performance. For example, Wigdor et al. [261] found that orientation of the control space with respect to the display space affected task performance while interacting with a large display in different seating positions. Wallace et al. [248] reported on performance loss due to the input redirection in a multi-display environment when users were seated not facing the display. Further research is needed to determine whether these disadvantages outweigh the benefits of using local input, and whether the degradation in performance is affected by cross-display switching.

3.3 The Scope of the Thesis & Taxonomy of MDUIs

In this thesis, we aim to explore the performance effects of attention switching using the visual arrangement of MDUIs shown in Table 3.5.

Table 3.5: Taxonomy of Prototypes Investigated in the thesis.

Display Contiguity	**Angular Coverage**	**Content Coordination**	**Input Directness**	**Input-Display Correspondence**
Visual field & Depth Discontiguous	Field-wide	Cloned (in Chapters 4 & 5), Coordinated (in Chapter 5)	Hybrid	Redirectional

3.4 Summary and Discussion

This chapter provides a brief overview of the existing taxonomies that are applicable to MDUIs and introduces a taxonomy of MDUIs based on the factors associated with the visual arrangement of UI elements that can affect cross-display switching during user interaction with MDUIs. The proposed taxonomy is described as comprising five factors, i.e., display contiguity, angular coverage, content coordination, input directness, and input-display correspondence. Some of the existing work containing MDUIs is classified based on these factors and the relevance of each factor to cross-display switching is discussed.

There are three principal means of acquiring knowledge... observation of nature, reflection, and experimentation. Observation collects facts; reflection combines them; experimentation verifies the result of that combination.

Denis Diderot

Chapter 4

Proximal and Distal Selection of Widgets for Mobile Interaction with Large Displays*

A smartphone can be used as a remote control for large displays such as personal computers [145, 150] and interactive TV (iTV) [41, 53]. As it is not practicable for the physical buttons on a typical remote control device to accommodate the sheer diversity of operations for interactive screens [135, 221], a viable alternative is to resort to mobile touchscreens as remote controls [40, 53]. However, the absence of physical buttons deprives the user of tactile feedback and he/she has to shift attention from the large display to the remote control. This may cause undesirable delays in the operation and consequently undermine the viewing experience. The other option is to place control widgets on the large display. However, this arrangement can cause visual clutter on the screen. Moreover, pointing at distant widgets is known to be imprecise due to hand jitter and the lack of a supporting surface [152].

*Some of the contributions presented in this chapter have also appeared in [181]. Jarmo Kauko assisted the first author in building the prototype, and Jonna Häkkilä and Aaron Quigley provided valuable feedback on the experiment design and oversaw the user study.

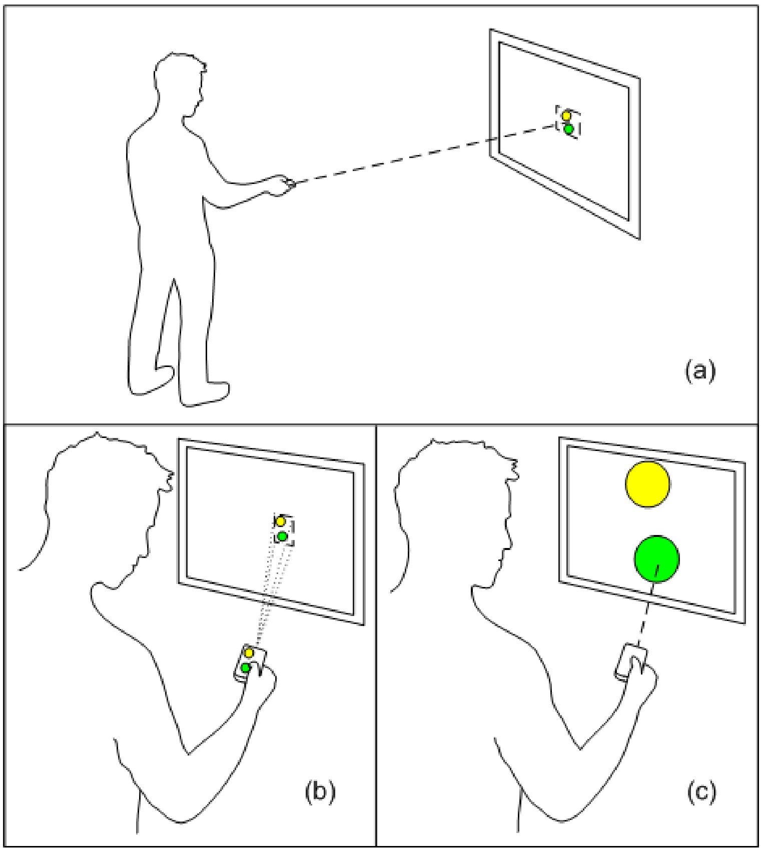


Figure 4.1: (a) Pointing at the Large Display (b) Proximal Selection (c) Distal Selection.

To date there is little information available on how the switching of visual attention due to the distribution of control widgets across the mobile device and the large display affects task performance. In this chapter, we report on an empirical study of how the *difficulty* of task affects the completion time and error rate in selection of multiple widgets with "no-attention-switch" vs. "attention switch" UI configuration. The results of this study are applicable to tasks that involve multiple widget selection (e.g., multiple item selection, adjusting the volume of a media file, searching in a hierarchical menu).

In this experiment, the difficulty of the task is adjusted by varying the *quantity* and *size* of the widgets. The "no-attention-switch" condition is reflected in the Distal Selection (DS) technique (see Figure 4.1c) that uses a mobile pointer to zoom-in to the region of interest and select the widgets on the large display. The "attention-switch" condition is reflected in the Proximal Selection (PS) technique (see Figure 4.1b) that involves pointing at the large display to transfer the zoom-in view of the selected region onto the mobile touchscreen, and switching attention towards the latter to make widget selections thereafter. With respect to the definitions considered in Section 2.1, the PS technique reflects a multi-display system and contains a multi-display user interface (MDUI). The DS technique reflects a multi-device system but not a multi-display system (visual output is shown only on the large display) and does not contain a MDUI.

The related work and the motivation for this user study are discussed in Section 4.1. The details of experiment design are explained in Section 4.2 and experimental results are presented in Section 4.3. Based on the discussion of these results, lessons for practitioners are outlined in Section 4.4 before the chapter is concluded in Section 4.5.

4.1 Related Work

Pointing is known to be a direct, user-friendly and intuitive gesture for selecting objects at a distance [203] and is commonly supported in remote control devices for TV and media players. Over the years, various researchers have explored the use of a mobile phone as a pointing device for interaction with distant displays [14, 34, 152]. Some of these experiments rely on the mobile phone's embedded cameras [14, 34] while others make use of laser [152] or infrared [32] pointing systems. However, selecting targets by physical pointing is known to be imprecise and slow due to hand jitter and the lack of a supporting surface [152].

The research community has proposed solutions to overcome the hand tremor problem associated with pointing devices. The usage of magnifiers is reported to have helped the users to read and interact with small buttons and hyperlinks on a display from a distance [176]. Forlines et al. [75] introduced the Zoom&Pick (ZP) technique that allows zooming-in to the region of interest to facilitate target selection with handheld projectors. Experimental results show that ZP improves the accuracy of target acquisition, although the increased complexity also results in longer pointing times. The DS technique used in this experiment was inspired by the ZP approach [75]; however, unlike their technique, DS uses a light-weight handheld prototype and interacts with a fixed display, rather than a projection that is itself prone to hand-jitter.

Myers et al. [152] suggested a "semantic snarfing" (SS) technique that uses a laser pointer to select the region of interest on the large display and then copies ("snarfs") the item to the user's handheld device. This technique is inspired by remote desktop solutions such as the Virtual Network Computing (VNC) system [196] that allows manipulation of a remote desktop display from a local display. The PS technique in this experiment was inspired by the SS approach [152]. Our work differs in that we compare PS with a direct pointing technique (i.e., DS) that also makes use of zooming-in before selection, and we compare both techniques under varying levels of task difficulty (i.e., quantity and size of widgets).

4.2 Experiment

4.2.1 Apparatus

The mobile device consists of a Nokia N900 handset attached to the circuit board of a Nintendo Wii™ remote control (Wiimote) as shown in Figure 4.2. The depth of the whole device is 2.7cm and its weight is 216g. We used a mobile phone charger to provide power for the Wiimote.

Figure 4.2: Mobile device: Wiimote circuit board attached to the back cover of N900 mobile phone.

The N900 has a resistive touch display of 7.6x4.5cm (3.5") with a resolution of 800x480px (267ppi). In addition, we used a 92.5x52cm (42") LG High Definition Liquid Crystal

Display^{TM} (LCD), with resolution 1920x1080px (54ppi), positioned at eye level and approximately 2.5 metres from the users. The LCD was connected to a PC running our test software and communicated via Bluetooth with the Wiimote as well as with the N900. The Nintendo Wii^{TM} sensor bar was placed on the top of the LCD. The brightness, contrast and refresh rate (i.e., the *how* characteristics described in Section 2.5.7) of the LCD were adjusted as much as possible such that the participants did not find them noticeably different from those of the mobile device.

4.2.2 Participants

The study was conducted with 20 participants: 17 males and 3 females, in the age group of 30–45. The participants were selected from our department based on the responses to our email advertisement. All of them had normal or corrected-to-normal vision. Among them, 3 were ambidextrous, 3 were left-handed, and the rest were right-handed. All participants had previous experience of using touchscreen phones and all except 2 (18/20) had also played with Nintendo Wii^{TM} . Each participant received a free movie ticket as a compensation after the experiment.

4.2.3 Task

Before starting the experiment, participants were given an introduction about the nature of task and interaction techniques to be tested in the experiment. This was followed by a practice session in which they held the mobile device in their dominant hand and rehearsed the task with both interaction techniques.

The task was to select a number of clustered circular widgets and consisted of two steps. First, the widget region was zoomed-in to by pointing with a rectangular cursor as shown in Figure 4.1a. Second, each widget was to be selected from the zoom-in view of the selected region. With the DS technique, the zoom-in view was shown on the large display and the widgets were selected by pointing as shown in Figure 4.1c. With the PS technique, the zoom-in view was shown on the mobile device and widgets were selected by touching thereafter as shown in Figure 4.1b.

All tasks were performed while sitting and by using the thumb of dominant hand only. Surveys confirm [95, 123] that users would generally prefer to use touchscreens with one hand when possible, hence, we decided to include a one-handed task in this study. We used circles as widgets because they have the same diameter in all directions, and that makes it easier to compare different widget sizes.

We used a rectangular region of 1757x1054px (82.6x49.6cm) to show contents on the LCD, matching the 15:9 aspect ratio of the N900 display. The zoom-in factor was 5x, corresponding to an area of approximately 351x211px (16.5x9.9cm) on the LCD. With the PS technique, the equivalent zoom-in region was shown on the N900. However, the zoom-in rectangle aspect ratio was 9:15 as the N900 was held in the portrait mode. We used scalable vector graphics to ensure that the zoom-in region was the same in both displays regardless of different native display resolutions. For each task, positions of widgets were randomised to fit inside the zoom-in rectangle.

We enabled panning in the zoom-in mode to make sure that all widgets were accessible, even if they were outside the initial zoom-in region. We instructed participants to select widgets as fast as possible without making too many mistakes. We also used a harsh error sound to discourage participants from sacrificing accuracy.

4.2.4 Design

The experiment used a within-subjects factorial design. The independent variables in the experiment were *interaction technique* (DS and PS), *widget quantity* (2, 4, 6 and 8 widgets) and *widget size* (small and large). Before zooming in, the diameter of the small widget was 36 pixels and that of the large widget was 54 pixels. In the mobile zoom-in view, diameters of small and large widgets were translated to 7.88mm and 11.8mm respectively. In the large display zoom-in view, diameters of small and large widgets were translated to 87.7mm and

131.5mm respectively.

We selected sizes of mobile widgets based on the results of a user study [169] that was meant to determine optimal target sizes for one-handed thumb use of the mobile touchscreen. The results showed that while speed generally improved with the increase in target sizes, there were no significant differences in the error rate between target sizes $\geq$9.6mm and targets $\geq$7.7mm in single-target (discrete) pointing tasks (e.g., activating buttons, radio buttons) and serial tasks (i.e., tasks that involve a sequence of taps (serial), such as text entry) respectively.

Each participant undertook 5 trials under all conditions. One trial consisted of zooming in to the widget region and successfully selecting all 2–8 widgets. The order of all conditions was randomised to mitigate any learning and fatigue biases. The design of experimental tasks (excluding practice sessions) was as follows: 2 *techniques* x 2 *widget sizes* x 4 *widget quantity levels* x 5 *repetitions* = 80 trials per participant. On average, each participant took 30 minutes for the whole experiment.

4.2.5 Hypotheses

The pre-experimental hypotheses are given below:

- *H1: The PS is a) faster and b) subjectively preferred over the DS.*

  We expected the PS to outperform the DS in terms of task completion time and subjective preference due to the advantages of touchscreen selection (i.e., supporting surface, less jitter, finer movements) over physical pointing.

- *H2: The speed difference between PS and DS is a) increased by the increasing the widget quantity, and b) decreased by increasing the widget size.*

  When there are more widgets to select, it would require more thumb movement with the PS and more wrist or arm movement with the DS, thus resulting in faster task completion with the former than with the latter. On the other hand, with small widgets, the greater effort required to make a precise selection, in addition to the overhead caused by the cross-display switching, will increase the completion time with the PS, thus reducing the speed difference between the PS and the DS.

- *H3: The PS and the DS are different in terms of error rate.*

  Both interaction techniques have different sources of inaccuracy, and are thus likely to differ in the error rate.

4.3 Experimental Results

4.3.1 Task Completion Time

After testing the normality of task completion times distribution, we analysed the data using a repeated measures ANOVA. Supporting our hypothesis H1-a, there was a significant main effect for the technique ($F_{1,19}$=77.5, p<0.001, η_p^2=0.80). Also, we found a significant interaction effect between the technique and the widget quantity ($F_{3,57}$=46.45, p<0.001, η_p^2=0.71). To analyse this interaction further, we conducted post-hoc analyses using pairwise t-tests with a Bonferroni correction. The post-hoc test shows that the effect of technique is significant for quantity levels 4, 6 and 8 (t_{39}=6.2, 8.9 and 9.1 respectively, all p <0.001). This indicates that PS outperforms DS in *difficult* tasks, as shown in Figure 4.3. For quantity level 2, the technique effect was insignificant, and in fact the mean task time for DS (3.28s) was less than that for PS (3.36s). This confirms our second hypothesis regarding the widget quantity (H2-a).

There were significant main effects for the size ($F_{1,19}$=123.78, p<0.001, η_p^2=0.87) and the quantity ($F_{3,57}$=531.72, p<0.001, η_p^2=0.97) of widgets. As expected, selecting large widgets (M=5.3, SD=1.9) was faster than selecting small widgets (M=6.5, SD=2.4). The task completion time increased almost linearly with the widget quantity, as shown in Figure 4.3. There was also a significant interaction effect between the widget size and the widget quan-

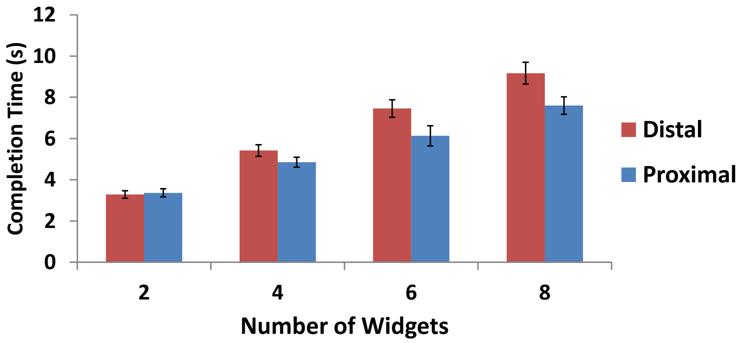


Figure 4.3: Completion time for different number of widgets with Distal Selection (DS) and Proximal Selection (PS). Error bars indicate 95% confidence intervals.

tity ($F_{3,57}$=30.0, p<0.001, η_p^2=0.61), but we did not analyse this further as it was not related to our primary hypotheses. Other significant main or interaction effects were not observed. Therefore, we cannot confirm that widget size would affect the speed difference between the PS and the DS techniques, hence, rejecting H2-b.

4.3.2 Error Rate

In our experiment, participants were not able to proceed to the next trial without selecting all the widgets, even if this required multiple clicks. Therefore, we calculated the error rate as the number of missed clicks per number of widgets. Note that this formulation would allow error rates higher than 100%. However, we did not observe error rates above 50% in any trials.

Most tasks (79%) were completed without any errors. The resulting error rate distribution based on the means of 5 trials resembled a half-normal distribution. As we did not have any appropriate transformation or non-parametric test available, we conducted the analysis using a repeated measures ANOVA. The sphericity was tested using Mauchly's test. Although ANOVA is known to be relatively robust against non-normal distributions, the results should be interpreted with caution.

We found a significant main effect for the technique ($F_{1,19}$=9.44, p<0.01, η_p^2=0.33) indicating that DS (M=4.0%, SD=5.5%) is more accurate than PS (M=7.8%, SD=10.5%). A significant main effect for the widget size ($F_{1,19}$=31.51, p<0.001, η_p^2=0.62) shows that the error rate for small widgets (M=9.4%, SD=10.5%) was higher than that for large widgets (M=2.4%, SD=3.7%). There was also a significant interaction effect between the technique and the widget size ($F_{1,19}$=13.44, p<0.01, η_p^2=0.41). The post-hoc analysis revealed that the technique effect was significant only for small-sized widgets, hence confirming H3. Figure 4.4 shows error rates for the techniques and widget size.

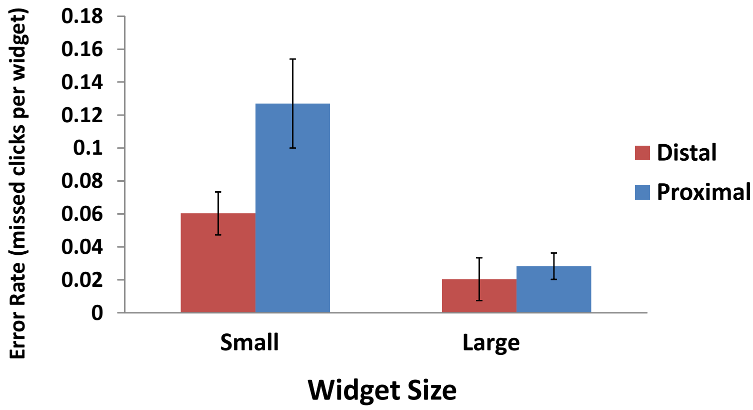


Figure 4.4: Error rate for Distal Selection (DS) and Proximal Selection (PS) with different widget sizes. Error bars indicate 95% confidence intervals.

4.3.3 Attention Switch Time

As the quantity of widgets had an approximately linear relationship with the task completion time, we used a simple linear regression to model the task completion time for both techniques. The completion time (in seconds) was modelled as *1.41+0.98*quantity* (R^2=0.86, $F_{1,78}$=491.42, p<0.01) for DS, and *1.99+0.70*quantity* (R^2=0.82, $F_{1,78}$=367.94, p<0.01) for PS. Both models are shown in Figure 4.5.

We calculated the value of attention switch time based on the difference between regression constants (i.e., intercepts) of both models (i.e., 1.99-1.41=0.58 seconds) and reported it in [181]. Further analysis of standardised residuals against standardised fitted values for DS

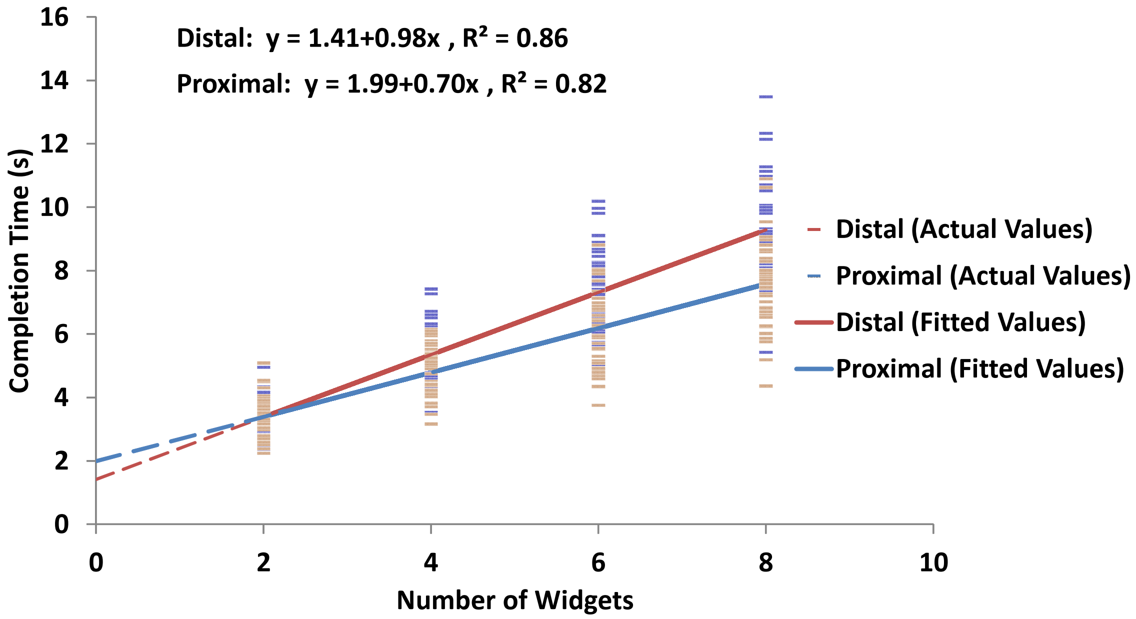
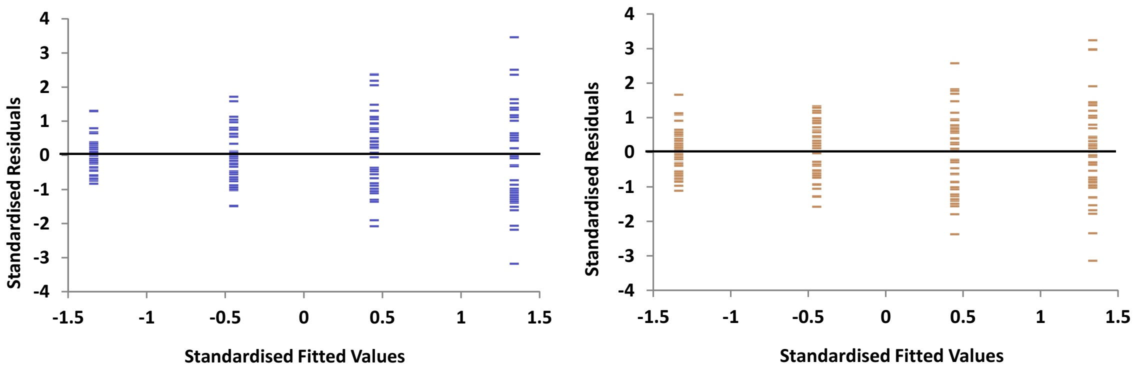


Figure 4.5: Scatterplot of completion time against number of widgets with regression lines for Distal Selection (DS) and Proximal Selection (PS).

(see Figure 4.6a) and PS (see Figure 4.6b) confirmed the evidence of a linear relationship (as indicated by the symmetric distribution of residuals around the zero line) but also suggested unequal variances (as indicated by the unequal spread of residuals at different fitted values). Therefore, we applied a linear mixed effects model [130] to model the completion time against the interaction between technique and widget quantity, while allowing for the increasing variance due to the increasing widget quantity. This model indicated a significant effect of the interaction technique (t_{297}=3.48, p<0.05) and calculated the attention switch time as 0.64$\pm$0.36 seconds.

Holleis et al. [99] calculated the time taken for a *macro attention shift* (i.e., switching attention between a mobile device and a real world object) to be 0.36 seconds. However, our work differs from theirs in terms of:

- Type of task. Their task involved switching attention between a mobile phone and a movie poster containing Near Field Communication (NFC) tags pasted on a wall.
- Number of participants. They tested 9 users.



(a) Distal Selection (b) Proximal Selection

Figure 4.6: Scatterplot of standardised residuals against standardised fitted values of completion time for Distal Selection (DS) and Proximal Selection (PS).

- Method of value calculation. They calculated the value using a frame-by-frame manual analysis of video tapes.

4.3.4 Subjective Evaluation

The participants rated each technique for each widget size in terms of their satisfaction with mental load, physical effort, speed, accuracy, and frustration level involved. All these aspects were rated on a Likert scale from 1 (strongly disagree) to 7 (strongly agree).

Since these ratings contain the ordinal data collected from a multi-factorial design (i.e., 2 *techniques* x 2 *widget sizes*), standards tests such as Wilcoxon Signed Ranks test are not applicable here because they support only a single factor non-parametric analysis [121, 266]. Therefore, we used a repeated measures non-parametric test with an Anova Type Statistic (ATS) [37] to analyse the results. As this test is not widely used in HCI and the usual practice is to use a repeated measures ANOVA for multi-factorial non-parametric analysis [121], we verified all significant results using a repeated measures ANOVA.

We discovered that the technique had a significant effect on the satisfaction level with the physical effort (ATS=4.4, $p<0.05$). This indicates that users were significantly more satisfied with the physical effort required for PS (median=6) than for DS (median=5), supporting our hypothesis H1-b.

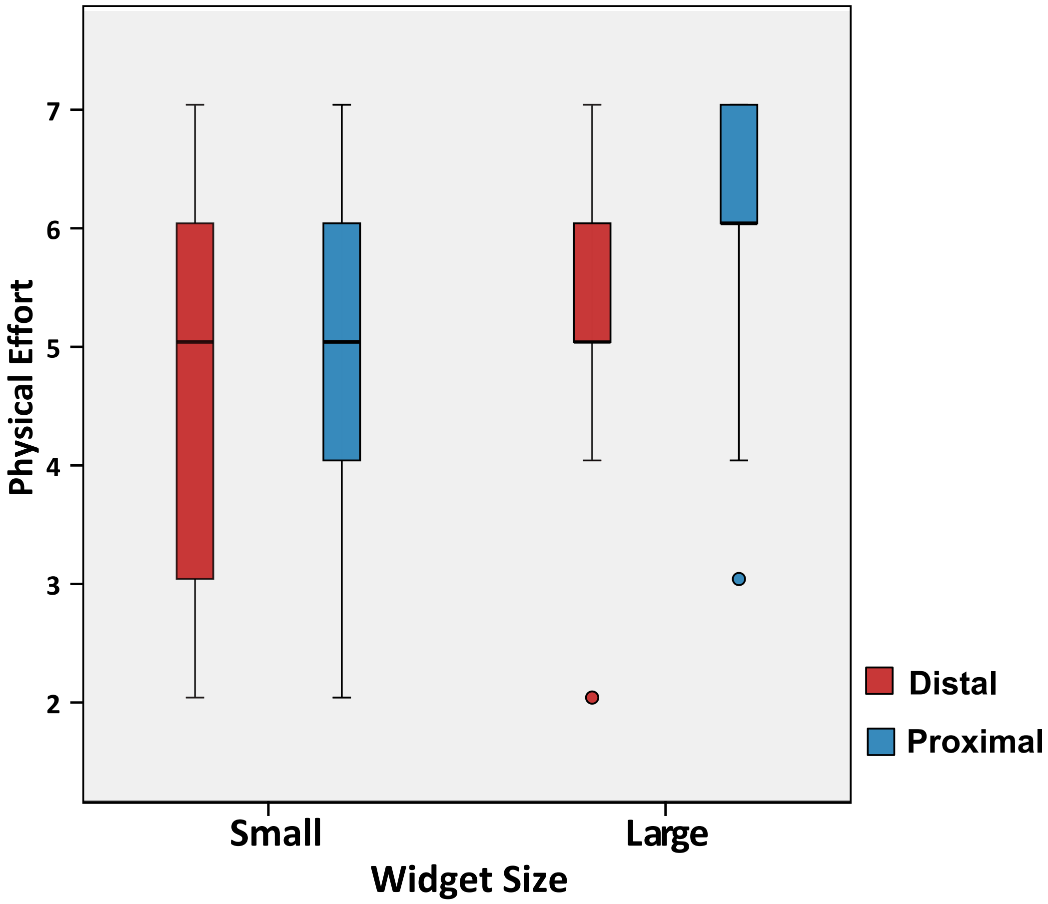


Figure 4.7: User ratings of the DS and PS techniques with respect to physical effort.

Ratings for physical effort are presented in Figure 4.7. The widget size had a significant effect on ratings for all questions (all $p<0.01$). Not surprisingly, participants rated large widgets more positively regarding all questions.

4.3.5 Overall Preference

Regarding overall preference, 15 participants (75%) selected PS while 5 (25%) selected DS as their favourite technique for selecting widgets on distant displays, hence confirming H1-b. Using a binomial test, this difference is found to be statistically significant ($p<0.05$). Some participants explicitly mentioned that the DS technique would be better for selecting a single widget. Most participants found it easier to accomplish the tasks with PS, however, they disliked the switching of visual attention between the mobile device and the large display. The DS technique was found to be more straightforward and fluent, but the repeated wrist movement became tiring and annoying with the increase in the number of widgets.

4.4 Discussion

Experimental results show that both interaction techniques are almost equally fast for selecting 2 widgets. However, as the number of widgets increases, PS becomes increasingly faster than DS. Most participants found the PS technique to be particularly useful for selecting many proximate widgets (e.g., adjusting the volume of a media file, selecting multiple menus and sub-menu items). They considered it easier to use the thumb on the mobile touchscreen for multiple selection than using the wrist and the arm with the pointing device.

On the other hand, the DS technique turns out to be the favourite technique for selecting few and sparsely placed widgets in a consistent and continuous manner. All the participants except one (19/20) found the visual attention switch between the mobile and the large display to be the biggest drawback of PS. As expected, DS was found to be more fluid in this regard. However, there was one participant who preferred switching attention across devices, rather than constantly staring at the large display.

The higher error rate of the PS technique can be attributed to the "fat finger problem" of touchscreens as the fingertips are likely to occlude small targets, thus depriving users of visual feedback during target acquisition [4].

4.4.1 Limitations

Although this study analyses the cost of cross-display switching in a multiple widget selection task, considering the relatively low cognitive load involved in the task, results might not be applicable to more cognitively demanding tasks (e.g., a visual search that requires filtering out the distractors before selection) where this cost is likely to be higher. Moreover, mobile touchscreens are increasingly being used as a trackpad to control the cursor on a distant display [145, 194]. How a trackpad selection technique performs in comparison with DS and PS techniques remains to be explored.

Although we tested circular widgets due to their uniform shape, this choice led to compromising some ecological validity of the experiment because the widgets on most display devices are usually rectangular or square in shape. A study shows that the shape of widgets affects their acquisition time [84]. Therefore, we assume that PS and DS techniques might give rise to different results when used to select widgets of other shapes.

The changing size and resolution of displays is likely to affect the results. For example, increasing the resolution of either display, while keeping its size unchanged, would make widgets appear smaller and more congested. That would necessitate finer movements with both PS and DS techniques, thus possibly altering the results of their comparative performance. Moreover, with the increasing distance from the large display, the performance of the DS technique is likely to degrade because a smaller degree of hand movement would cause larger angular movement that would make it harder to select widgets [127].

We recruited our participants using opportunity sampling. The participants were in the age group of 30–45; all of them had normal or corrected-to-normal vision and most of them were familiar with the use of smartphones, Nintendo Wii™ and large displays. The same experiments with elderly people or people with near-sighted or far-sighted vision might yield different results with the PS and DS techniques.

4.4.2 Lessons for Practitioners

The results of this study are useful in designing UIs for tasks that require multiple widget selection (e.g., multiple item selection, adjusting the volume of a media file, search in hierarchical menu structure). Based on our experimental results, we provide the guidelines for practitioners as follows.

- Direct pointing (as exemplified in the DS technique) is faster if there are two widgets to be selected in series.
- With the increasing number of widgets to be selected in series (e.g., in a task involving multiple item selection), the faster performance of the PS technique overcomes the cost of initial cross-display attention switching.
- Moving user interaction from the large display to the mobile device should better save the user considerably more than 0.64 ± 0.36 seconds (i.e., the time cost of cross-display switching), otherwise it is better done on the large display, i.e., under "no-attention-switch" condition.

4.5 Conclusion

This chapter presents an empirical comparison of the task performance for selecting multiple widgets in the "no-attention-switch" vs. "attention switch" condition. The "no-attention-switch" condition is exemplified in the Distal Selection (DS) technique that uses a mobile pointer to zoom-in to the region of interest and select widgets on the large display. The "attention-switch" condition is exemplified in the Proximal Selection (PS) technique that involves pointing at the large display and transferring the zoom-in view of the selected region onto the mobile touchscreen for widget selections. Experimental results confirm our hypothesis that PS is preferable in tasks involving a higher number of widgets as it is faster and requires less physical effort. In tasks involving selection of two widgets, DS is as fast as PS and generates fewer errors. As it does not require switching of visual attention between the mobile device and the large display, it gives a more fluid and uninterrupted user experience. The time cost of switching attention across the mobile device and the large display has been calculated to be 0.64 ± 0.36 seconds in the aforementioned task. The results of this study are applicable to the design of UIs for tasks that require multiple widget selection in series (e.g., multiple item selection, adjusting the volume of a media file, search in a hierarchical menu structure).

No amount of experimentation can ever prove me right; a single experiment can prove me wrong.

Albert Einstein

Chapter 5

Visual Search with Mobile, Large Display and Hybrid Distributed UIs*

A major drawback of mobile devices is that their screens do not allow for displaying large amounts of information at once [46] without requiring interaction, thus restricting the possibilities for information access and manipulation with these devices. One attractive approach used to address this problem is to complement the small display of a mobile device with a larger display, which might be borrowed opportunistically from the environment (see Figure 5.1 and [179]). Such configuration has several perceived advantages, including:

- The large display might supplement the screen real estate lacking in the mobile display.
- Input can still be provided through the mobile device, which is familiar to, proximate to and easily manipulated by the user.
- Implementation of this kind of configuration is already possible with a currently available infrastructure (e.g., network-connected digital signage [101]).

*Some of the contributions presented in this chapter have also appeared in [183]. Miguel Nacenta assisted the first author in the experiment design, and Aaron Quigley provided valuable feedback on the experiment design and oversaw the user study.

Many research projects (e.g., [34, 45, 60, 62, 69, 80, 81]), and numerous new commercial products (e.g., Wii U [262], Apple Remote App [145], multi-device Scrabble [211]) point to a future where we might expect operating-system-level support for multi-display ecosystems with seamless interaction across opportunistically available displays. However, before this can happen, we need to better understand the implications for task performance when the interface to an application exists across multiple displays. Indeed, the distribution of the interface may introduce new problems that are not present in single-screen user interfaces [156, 230] and we need to know whether the added problems outweigh the advantages of the extra display.

Figure 5.1: Hybrid Configuration for Information Seeking.

In this chapter, we describe a series of experiments that investigate the effects of three UI configurations (mobile-only, mobile-controlled large display, and hybrid) on performance, subjective workload and user preference in three tasks common to mobile scenarios (map, text, and photo search). According to the definitions given in Section 2.1, the hybrid configuration exemplifies a multi-display system that contains a multi-display user interface (MDUI). The other two configurations do not contain MDUIs as a mobile-controlled large display is a multi-device system, but not a multi-display system, and a mobile-only configuration represents a single-display system. Both the mobile-only and the mobile-controlled large display configurations signify the "no-attention-switch" condition while the hybrid configuration represents an "attention-switch" condition.

We discuss the related research and distinguish our work from it in Section 5.1. The empirical conditions that were common to all experiments are described in Section 5.2. The individual details of each experiment and the results are discussed as follows: map task in Section 5.3, text task in Section 5.4 and photo task in Section 5.5. The implications of experimental results are discussed in Section 5.6 before the chapter is concluded in Section 5.7.

5.1 Related Research

5.1.1 Distributed and Multi-device User Interfaces

Several research groups have explored multi-display environments that use a large situated display to complement a mobile device (mobile+large display) [62, 238]. Some prototypes demonstrate varied applications where the mobile device is used for both input and output [45, 60, 82, 101, 149, 181, 190], or exclusively for input [15, 101, 131, 139]. LensMouse [270] is also an example of this kind of configuration, although it is actually meant to be an enhanced input device for personal computers.

5.1.2 Studies on Distributed Interaction

Although many mobile+large display systems exist with alternative distributions of input and output, comparisons of the effects of different configurations are scarce.

ARCPad [139] and LensMouse [270] contain evaluations of pointing and menu access capability; although these are useful for the design of input interaction techniques, this work seeks to investigate higher-level tasks that go beyond selection. Finke et al. [69] investigate several strategies for the design of applications across personal and public displays and test several examples; however, these provide qualitative evidence about specific applications that might be difficult to generalise, and they did not find differences between configurations. Closest to the present research is the study by Gostner et al. [80], which investigated a text search and entry task using large display-only, mobile-only, and hybrid configurations and found that the large-display and hybrid condition were best. This study extends their work in three ways: it tests three tasks (map, text and photo search), it isolates the text search (which they studied in combination with text entry), and it considers a large display configuration that is comparable in input to the hybrid and mobile-only configurations (their large display condition had input in the large display, which could introduce a confound as the results could be due to input or output differences).

Although the studies are not identical, the results from research on projector phone devices are also relevant to this study. Hang, Rukzio and Greaves [81, 91], studied picture browsing and map search tasks, finding performance advantages for the projected-only configuration for their map search tasks. Besides the differences in the physical environment (theirs was a hanging mini-projector attached to a mobile phone), this work differs from theirs in two main ways: it uses touch as input (they used buttons and a joystick), and it provides a statistical analysis of differences in performance and user preference. Cauchard et al. [39] studied the effects of the positioning of the projected image on hybrid (mobile+projected display) configurations. They found that having the two screens in the same visual field encouraged context switches, but that did not affect task performance. A study concerning dual-view visualizations shows that the time cost for context switching may not be significant [50].

5.1.3 Issues in Mobile-Large Display Interactive Scenarios

Other researchers have investigated issues that are relevant, but they focused on other scenarios. For example, mobile+large display configurations can be considered to be bifocal display systems and used for overview and detail [48]. Grudin [85] highlights how the partition between displays can be beneficial; Tan et al. [230] showed that comparing information across displays at different depths has a small cost in terms of performance; and Bi et al. [29] found that bezels can negatively affect the visual search in vertical displays if objects are split. Finally, map navigation in large displays was found to be more efficient with physical navigation than through panning and zooming [11].

5.2 Empirical Study

Three studies, testing three different tasks, were designed. The main goal of the studies is to find out which UI configuration is best and worst for each task in terms of performance, subjective workload, and participant preference. The secondary goal is to investigate the possible causes of these results. We chose tasks among those identified as the most common information tasks performed on mobile scenarios: a map search, text search, and photo search [46]. Elements common to all three experiments are described in the following subsections. Specifics of each experiment are explained in their corresponding experiment sections.

5.2.1 Apparatus

The apparatus consisted of two displays: a HTC Desire HD™ mobile device with a 480x800 px (240ppi), 5.7x9.6cm (4.3") screen and a 1920x1080px (54ppi), 92.5x52cm (42") LG High Definition Liquid Crystal Display™ (LCD). The large display was attached to a Windows 7™ PC and both devices ran custom experimental Java™ software connected through a IEEE 802.11 wireless connection with no perceptible delay. The brightness, contrast and refresh rate (i.e., *how* characteristics described in Section 2.5.7) of the LCD were adjusted as much as possible such that the participants did not find them noticeably different from those of the mobile device.

Participants sat on a chair, with the large vertical display perpendicular to them and centred in front, at a distance of approximately 120cm. Participants were not movement constrained although we kept the chair in a fixed position. In pilot tests, we observed some participants preferred holding the mobile device in their non-dominant hand and using their dominant hand for interaction, due to the relatively large screen size of the mobile device. Therefore, to maintain consistency in our results, we asked all participants to hold the mobile device in their non-dominant hand and use the index finger of the dominant hand for interaction. Participants were allowed to hold the untethered mobile device in the non-dominant hand freely, but always in a portrait orientation. The automatic screen rotation in the mobile device was disabled to prevent any change in the presentation style of the contents due to hand tremors. All trials were video recorded and encoded with respect to each task and UI configuration. We used a Sony Handycam NEX VG10E camera that was fixed on a tripod stand and its position was adjusted such that the participants' eye and head movements across mobile device and large display were clearly visible.

5.2.2 Conditions

The main factor for all three experiments was the UI configuration. Three UI configurations were studied as follows:

- *Mobile*. Only the mobile device was used for input and output. The panning and paging through touch input allowed virtual navigation of data space that did not fit on the mobile screen simultaneously.
- *Large Display*. The mobile device was used only as an input device; the output was shown only on the large display. The input was captured through a modified version of RemoteDroid [194] which works like a buttonless touchpad.
- *Hybrid*. The mobile device was used for input and output as in the mobile configuration, but the output was also shown on the large display. In the case of a large data size, the large display showed all the data, while the mobile device only showed a partial view. That part of the data visible on the mobile device was dynamically represented with the scope window frame, a rectangular bounding box on the large display (Figure 5.2).

The resolution and input ratio were kept constant across the three configurations. Each map, photo and text was represented by the same amount of pixels regardless of the display. The input was calibrated so that the same drag gesture would result in the same amount of pixel

Figure 5.2: Map search task on mobile and large display (hybrid configuration). Devices are not to scale.

movement. The control-display (C-D) gain was approximately 4.6 for mobile-controlled movements on the large display and 1 for the content on the mobile display (direct touch).

The secondary factor in all three experiments was the *data size*, which had two levels: *small*, and *large*. The small data was calculated to fit completely on the mobile display, while the large data did not, requiring some kind of navigation dependent on the task.

5.2.3 Measures

All experiments measured:

- *Completion time (CT)*. This was calculated from the time the trial started until the last selection was made.
- *Errors*. The proportion of trials with incorrect answer(s).
- *Length of interaction (LI)*. The finger drag distance logged by the mobile screen (in pixels) during the trial.
- *Gaze shifts (GS)*. The number of times a participant shifts gaze, or gaze and head pose, between displays, per trial. The experimenter examined the recorded video of each trial with hybrid UI configuration to count gaze shifts. These measurements were done twice to ensure accuracy.

- *Subjective Workload*. For each configuration and task, participants filled in a six-question NASA TLX [94] survey.
- *Overall Preference*. The participants ranked each configuration for each task in the order of their preference.

5.2.4 Participants

Twenty-six participants (age 19–33, 7 females) were recruited from the local university, using an email advertisement, in exchange for a compensation of £5. All participants had normal or corrected-to-normal vision. Except two, all had experience with touchscreen phones. Each participant performed all three experiments.

5.2.5 Procedure

Participants rehearsed with each UI configuration and data size before real trials. For each task, they performed three blocks of eight trials, each with a different UI configuration. The order of the experimental conditions was balanced across participants, although each participant would see the same order of configurations across all three experiments. Within each block, participants performed four trials under small data condition followed by four trials under the large data condition. The first and fifth trial in each block were considered to be training trials and are excluded from the analyses. Participants performed a total of 8x3x3=72 trials, of which 18 (25%) were considered as training. After each block, participants filled in the NASA TLX questionnaire, and after each experiment they were asked to rank the configurations in order of preference. Each study session took approximately 1 hour.

5.2.6 Data Filtering

We filtered out the data of participants that did not comply with a set of criteria established before the analysis. We discarded a participant's data for an experiment when more than 2/3 of the trials contained at least one error, when the participant showed signs of not understanding the task during the real trials, and when a significant disruption took place during the test (e.g., loud noise from outside).

5.3 Experiment: Map Search

This task represents map search situations where a user needs to find a location based on a choice criterion (e.g., the cheapest hotel) and is modelled upon map search tasks in other experiments [11, 91, 201]. It is representative of the object-locating task that is identified as one of the elementary tasks in mobile map interactions [187].

The participants had to find and tap on the marker with the lowest price label out of 15 markers distributed on the map. The map was shown on a fixed zoom level. We disabled the zooming function of the map interface primarily for two reasons, i.e., to mitigate any confounding effect of differences in map search strategies of different participants, and to avoid the overlap of markers and associated price values; each marker and its price value was distinctly visible on a particular zoom level, and zooming out would have collapsed them into each other.

The trial did not finish until the unique lowest-price marker was tapped. For the small data, all markers were visible within the mobile screen and the panning function was disabled.

In trials with large data, the markers were spread out across the full map, which was the same size as the large screen (1920x1080px), and was accessible from the mobile device through standard 2D panning. In the hybrid condition, a rectangle on the large screen dynamically represented the viewport currently shown on the mobile display (see Figure 5.2).

To keep the comparison fair across different UI configurations, we did not make use of any on-the-margins visualization of off-screen objects [24, 88, 273]; some of these visualizations have been shown to have improved performance in map tasks (e.g., planning routes or locating points of interest) with mobile maps [38]. It is possible that these techniques might bring a mobile interface on a par with the large display for the map search. However, considering our focus on the impact of cross-display switching on task performance, we deemed it appropriate to experiment with the baseline conditions of UI configurations, thus avoiding any confounding effect of off-screen object visualization.

5.3.1 Hypotheses

We formulated the following hypotheses about the results of the map search experiment.

- *H1. Under the small data condition, we will notice equivalent performance between the mobile and the large display configurations.*

  Under the small data condition, the whole data was simultaneously visible on the mobile device (in mobile configuration), and on the large display (in large display configuration). Therefore, we did not expect any performance differences between these configurations under this condition.

- *H2. Under the small data condition, the hybrid configuration will perform worse than both the mobile and the large display configurations.*

  Under the small data condition with hybrid configuration, there was little advantage of using the large display since it did not show any content that was not simultaneously visible on the mobile device. On the other hand, cross-display switching could cause an overhead that could worsen task performance compared to that with the mobile and large display configurations.

- *H3. Under the large data condition, both a) the large display and b) the hybrid will outperform the mobile configuration.*

Large displays have been shown to improve performance in spatial visualization and navigation tasks [12, 231, 232]. More room to utilise the peripheral vision, and to facilitate the physical navigation and embodied interaction [12] would suggest that the large display and hybrid configurations will outperform the mobile configuration for the map task under the large data condition.

- *H4. Under the large data condition, the large display will outperform the hybrid configuration.*

  We expected the cross-display attention switching in the hybrid configuration to cause an overhead, thus making it perform worse than the large display configuration. Hornbaek et al. [100] compared zoomable user interfaces with and without an overview for browsing tasks on two maps on a desktop display. The subjects were faster using the interface without an overview when using one of the two maps. Subjects who switched between the overview and the detail windows took more time, suggesting that the integration of overview and detail windows adds complexity and requires additional mental and motor effort.

  In their experiment, overview and detail windows were shown on the same screen while in the hybrid configuration we tested, the overview (the whole view) was visible on the large display and the detail (partial view) was viewed on the mobile device, hence requiring more physical movement, and more time, for attention switching. Although the distribution of input and output across displays in our experiment differed from theirs, we expected similar overhead due to switching attention between two views, thus suggesting better performance in the large display configuration than in the hybrid one.

- *H5. Under the large data condition, participants will prefer the hybrid configuration over the mobile and the large display.*

  In the same study [100], it was found that even though the participants performed faster using an interface without an overview, 80% of them preferred the interface with an overview, stating that it supported navigation and helped keep track of their position on the map. We expected similar responses from the participants of our experiment.

5.3.2 Results

No participant data was excluded for the map experiment.

Performance

The main measure of the experiment was the completion time. Due to the non-normality of the time measure distributions, all time statistical analyses were performed on log-transformed measures. Average times and graphs are presented in non-transformed measures (seconds). The same applies to the results of the next two experiments.

An omnibus ANOVA with the *configuration* and the *data size* as main factors and the *participant* as a random factor revealed a strong effect of configuration ($F_{2,50}$=11.29, p<0.001, η_p^2=0.31), and data size ($F_{1,25}$=84.93, p<0.001, η_p^2=0.77) on the completion time, as well as on the interaction between the two main factors ($F_{2,50}$=11.77, p<0.001, η_p^2=0.32). To follow up the interaction, we performed separate analyses on the large and small data conditions.

An ANOVA test on the small data trials showed that configuration had a significant effect on completion time ($F_{2,50}$=6.28, p<0.01, η_p^2=0.20). For the small data condition the mobile was the fastest configuration (M=8.99s), followed by the large display (M=9.29s, 3.3% slower) and hybrid (M=11.49s, 28% slower). Post-hoc tests corrected for multiple comparisons (Tukey's HSD) showed statistically significant differences between the hybrid (the slowest) and the other configurations, but not between the mobile and the large display.

The ANOVA test on the large data trials was also significant for configuration ($F_{2,50}$=18.45, p<0.001, η_p^2=0.42), but post-hoc comparisons show a different pattern, where the large display is significantly faster (M=11.17s) than both the hybrid (M=14.01s, 25% slower) and the mobile (M=16.52s, 47% slower) configurations. Figure 5.3 shows a summary of the mean completion times while Figure 5.4 shows a scatterplot of completion times, with different UI configurations and data sizes for the map task.

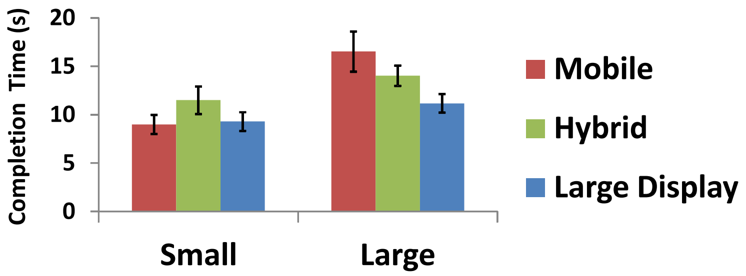


Figure 5.3: Map search: mean completion times with different UI configurations and data sizes. Error bars indicate 95% confidence intervals.

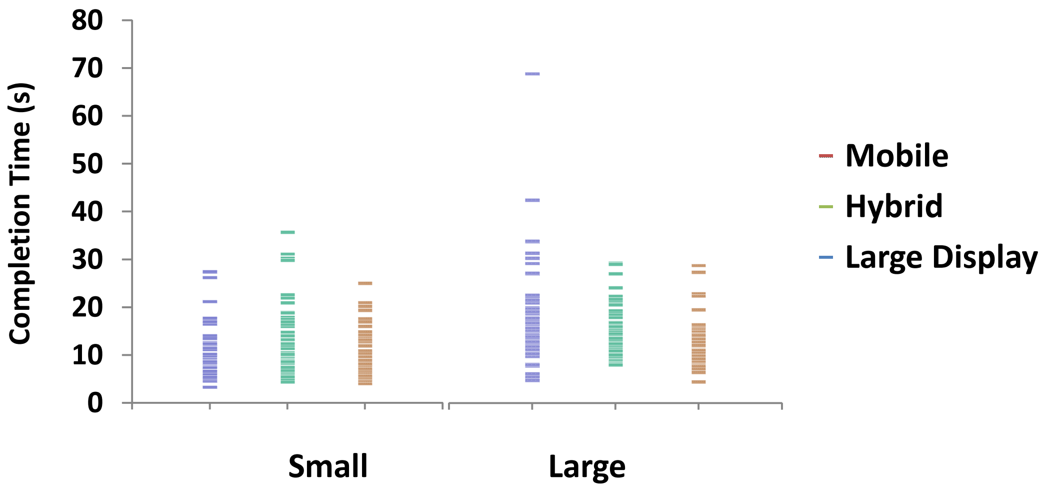


Figure 5.4: Map search: completion times with different UI configurations and data sizes.

Error data was strongly non-parametric and was analysed using a Friedman test, which showed no statistically significant differences between UI configurations ($\chi^2(2)$=4.23, p=0.12). The average number of trials with errors was lowest in large display (M=17.3%) followed by the hybrid (M=18.3%) and mobile (M=24.5%) configurations.

Subjective Evaluation

The 10-point scale NASA TLX questionnaire questions were analysed separately using non-parametric Friedman paired measures tests. We found significant differences among the UI configurations regarding physical demand, temporal demand, performance, effort and frustration level, but not for the mental demand (see statistics and averages in Table 5.1). The ratings show that participants ranked the large display as best across all subjective workload questions and the mobile as worst, with the hybrid in the middle.

Table 5.1: Map search: average ratings and statistics for the TLX questions. For performance, higher means better.

Factor	χ^2**(2)**	**p**	**Mobile**	**Hybrid**	**Large Display**
Physical Demand	11.06	<0.01	2.98	2.58	2.27
Mental Demand	5.01	0.08	2.75	2.19	2.21
Temporal Demand	9.32	<0.01	2.9	2.33	2.27
Performance	7.27	<0.05	7.85	8.42	8.75
Effort	6.93	<0.05	3.36	2.92	2.48
Frustration	8.44	<0.05	3.17	2.38	2.07

In the overall ranking, the mobile was overwhelmingly the least preferred configuration (for 17 out of 26 participants, 65%). The large display and hybrid configurations were ranked similarly (both were preferred by 12 participants), although the hybrid was more often the intermediate choice. The complete preference choices are displayed in Table 5.2. A Friedman test of these rankings shows significant differences between the three configurations (χ^2(2)=12.0, p<0.01).

Table 5.2: Map search: configuration preference rankings.

Configuration	**Best**	**Middle**	**Worst**
Mobile	2	7	17
Hybrid	12	11	3
Large Display	12	8	6

Comments from the participants served to further explain the preference rankings. The large display configuration was preferred to the hybrid one because the former did not require switching attention between displays. Participants who preferred the hybrid configuration often appreciated the availability of both detail and overview in the different displays. They also highlighted the ability to easily keep track of the overall position as one of the advantages of hybrid vs. mobile. The extensive panning required was cited as a disadvantage for the mobile configuration, although not for the hybrid configuration.

Auxiliary Analyses

In addition to the measures analysed above, we collected gaze shift and length of interaction measures to explore explanations for the differences in performance. Note that these analyses are not the main focus of the study and should be interpreted and generalised with caution.

An omnibus ANOVA of the length of interaction with the configuration and the data size as main factors, and the participant as a random factor, yielded the main effects of data size ($F_{1,25}$=118.79, p<0.001, η_p^2=0.83) and configuration ($F_{2,50}$=97.56, p<0.001, η_p^2=0.80), as well as indicating an interaction between the two ($F_{2,50}$=105.25, p<0.001, η_p^2=0.81). A post-hoc analysis analogous to the one performed above showed statistical differences between the interaction length in pixels between the mobile (M_{small}=2381px, M_{large}=39278px) and the other configurations (large display: M_{small}=849px, M_{large}=1270px; hybrid: M_{small} =645px, M_{large}=2361px), but not between the hybrid and the large display. Figure 5.5 illustrates the length of interaction with different UI configurations and data sizes.

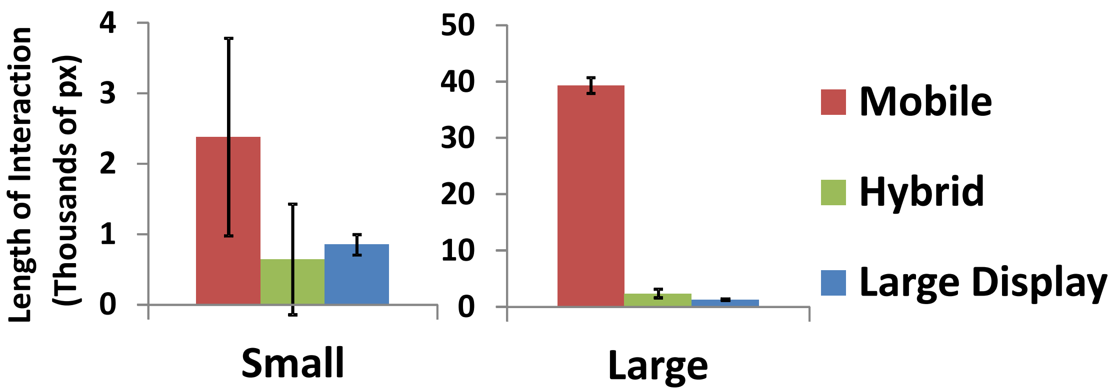
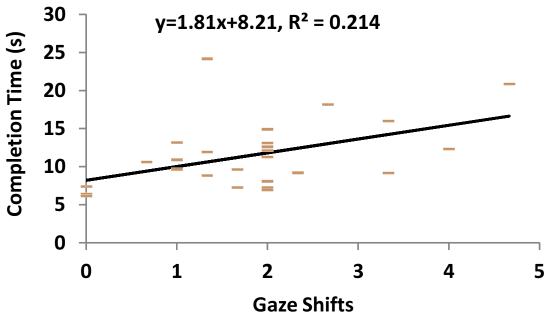
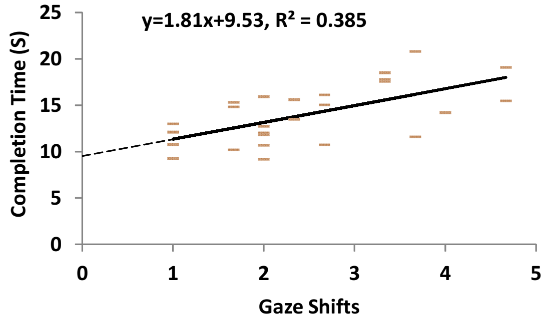


Figure 5.5: Map search: length of interaction (LI) with different UI configurations and data sizes. Error bars indicate 95% confidence intervals.

To investigate the relationship between gaze shifts and the completion time, we ran a simple linear regression test for the data in the hybrid configuration (which was the only one with gaze shifts). Trials from the small and large data were analysed separately to avoid causing the regression to appear significant due to differences in task requirements.



(a) Small Data



(b) Large Data

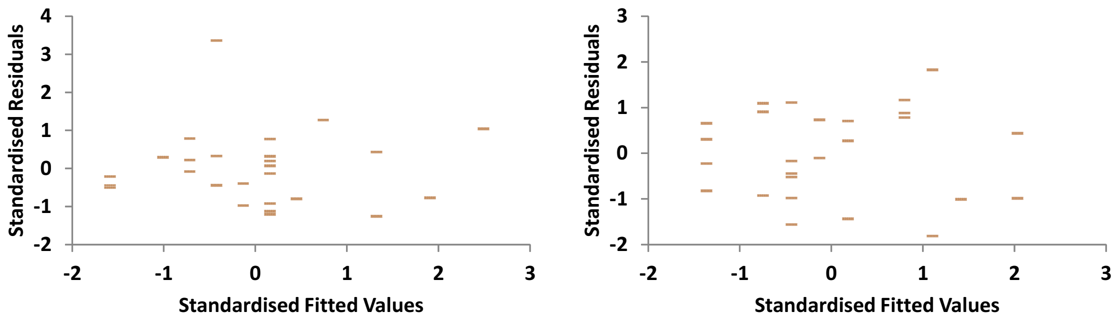
Figure 5.6: Map search with hybrid configuration: scatterplot of completion time against average gaze shifts (per trial).

For the small data, there is a linear relationship between the number of gaze shifts (#GS) and completion time (CT(seconds)=1.8*#GS+8.21; 95%CI=± 1.4), as shown in Figure 5.6a. This regression is statistically significant ($F_{1,25}$=6.55, p<0.05) and explains 21% of the completion time variance (R^2=0.214).

For the large data, the regression is very similar (CT=1.8*#GS+9.53, 95%CI=± 0.96), and also significant ($F_{1,25}$=15.01, p<0.01), although it explains a larger portion of the CT variance (R^2=0.385, 38%) as shown in Figure 5.6b.

The plots of standardised residuals against standardised fitted values of completion time for the small and the large data are shown in Figure 5.7a and Figure 5.7b respectively. The essentially shapeless patterns of these plots confirm the evidence of linear relationship and equality of variance, for both the small and large data conditions.

Since the participants in our study were free to make attention switches on their discretion, some of them chose not to switch at all, and focused only on the mobile interface, under the small data condition. That is the reason we get a higher confidence interval of the regression slope under the small data condition.



(a) Small Data (b) Large Data

Figure 5.7: Map search with hybrid configuration: scatterplot of standardised residuals against standardised fitted values of completion time.

5.3.3 Summary

In the map search, UI configuration made a large difference to task performance; for small data (i.e., data that fits within a mobile screen), mobile and large display are equivalent (thus confirming H1), and better than hybrid (thus confirming H2), whereas for large data (i.e., data that fits within a large display), the large display is faster than the hybrid (thus confirming H4) and mobile (thus confirming H3a). No significant differences were found between mobile and hybrid configurations for the large data, thus negating H3b. The overall disadvantage of the hybrid condition seems to stem from the gaze shifts needed in this configuration. Our measures indicate that each shift might cost up to 1.8 ± 1.4 seconds with the small data, and 1.8 ± 0.96 seconds with the large data. The auxiliary analyses suggest that, for the small data task, the main factor influencing performance was gaze shifts, which made the hybrid the worst UI configuration. The large data forced participants to pan much more in the mobile condition, making it the slowest; although this increased level of interaction was not necessary with the hybrid configuration (which showed low length of interaction), the gaze shifts in this configuration still mattered, making hybrid and mobile equivalently slow for different reasons. These results confirm the large display configuration as the best option across all data. Although this was recognised in the subjective workload assessments of participants (the large display ranked as the least demanding configuration), more participants ranked hybrid above large display (thus confirming H5) than the opposite when asked for their overall preference.

5.4 Experiment: Text Search

This task is representative of tasks that involve locating relevant fragments of text in informational texts (i.e., "nonfiction or expository texts" [212] as opposed to fictional or narrative texts). Such tasks are common in schools and workplaces [64, 89] and may include searching for particular extracts in a digital document or finding a relevant webpage-descriptor among a list of web search results.

The participants had to find and tap on the page-result descriptors that contained a specific text fragment. The text fragment was presented at the top of the displays and was reproduced verbatim within the target page-result descriptors. Our main focus in this experiment was to explore the effects of cross-display switching in the visual scanning of text. Therefore, we included a task that involved locating verbatim declarations because this task, being easier than tasks that require finding information that is not explicitly stated [164], is less susceptible to variance in results due to possible differences in participants' information seeking strategies. While our experimental design choice made it easier to measure task performance in an experimental setting, we acknowledge that it compromises some ecological validity with respect to more complex text search tasks. However, we have no sound reason to expect any differences in the task performance among UI configurations due to the tasks that require locating verbatim versus non-verbatim declarations.

The webpage-result descriptors were arranged in columns (see Figure 5.8). They consisted of text fragments from Wikipedia featured articles; text fragments were on average 30 words long, and had Flesch readability scores [72] between 50 and 62 (average score 56), which characterises text at 10th–11th grade reading level.

The text was left-aligned and shown in 12-point Sans-Serif font. Eye tracking studies have shown that variations in font sizes influence eye-fixation durations and saccade movements

[242]. The body text is recommended to be in 9–12 points; text sizes smaller than 9 points and bigger than 12 points are difficult to read because the former make it difficult to recognise words [51] and the latter force readers "to perceive words in sections, rather than a whole" [242] and slow down the reading speed. Pilot tests showed that the participants were comfortable when reading 12-point text on both the mobile device and the large display.

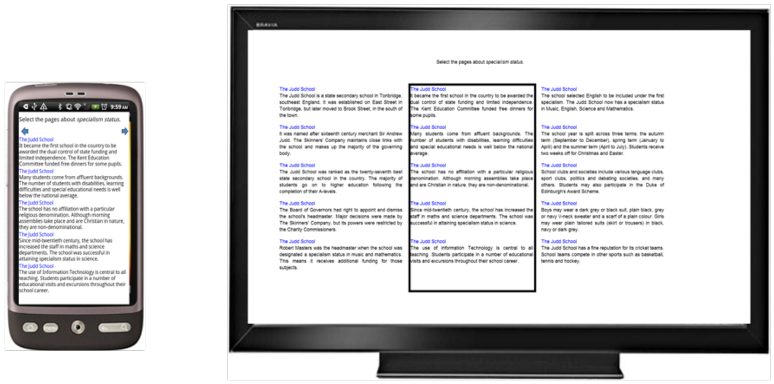


Figure 5.8: Text search task shown on mobile and large display.

Each page-result text was 23x31cm on the large display, and 5.6x9cm on the mobile screen, using a similar number of pixels across both displays. The search fragments to be found were, on average, 3 words long, i.e., the typical length of a query for a mobile web search [119].

In the small data condition, participants had to select one page-result out of five displayed in a single column. In the large data, participants had to select three page-results containing the specified text from among fifteen possible answers. Under the mobile and hybrid conditions, the fifteen page-result texts were distributed over three pages. Two arrows at the top of the small screen indicated the presence of another page to the left, to the right or both (see Figure 5.8). Switching between pages was possible through the standard horizontal swipe gesture implemented in most modern touch devices. Paging was chosen over scrolling for three reasons: evidence shows that paging is better for reading text on small screens [166, 172]; pilot tests showed that three pages were easier to navigate than a continuous vertical scroll; and, horizontal paging makes the large display configuration more equivalent in terms of control and visual configuration to the other two. Selection under the large display condition was achieved using a visible cursor controlled using the mobile device as a buttonless trackpad. We considered alternative mechanisms based on block-selection (without a visible cursor) but we found that these were less familiar and users performed worse in the three participants' pilot tests.

5.4.1 Hypotheses

We expected Hypotheses H1 and H2 as described in Section 5.3.1 also to be valid for the text search task. Additionally, we formulated the following hypotheses specific to this experiment:

- *H6: Under the large data condition, we will notice equivalent performance between the mobile and the large display configurations*.

  This hypothesis was based on the fact that the span of the human Useful Field of View (UFOV) changes according to the task, as discussed in Section 2.5.5. For tasks that require detailed discrimination, such as reading text, the UFOV covers only a fraction of the fovea. For readers of the English language, the span extends from 3–4 letters to the left of fixation to about 14–15 letter spaces to the right of fixation [185]. Based on these facts, we hypothesised that the wider visual field offered by the large display would not be particularly helpful in the text reading task.

- *H7. Under the large data condition, the hybrid will perform worse than both a) the mobile and b) the large display*.

  We expected this result due to cross-display attention switching in hybrid configuration.

5.4.2 Results

In this experiment we excluded the data from four participants according to the a priori criteria.

Performance

An omnibus ANOVA with configuration and data size as the main factors and the participant as a random factor revealed the strong effect of configuration ($F_{2,42}$=11.22, p<0.001, η_p^2=0.35), and data size ($F_{1,21}$=943.77, p<0.001, η_p^2=0.98) on completion time. Because no interaction was found between configuration and data size ($F_{2,42}$=1.42, p<0.05, η_p^2=0.06), we performed the post-hoc analysis of small and large data tasks together.

For the text task, the mobile was the fastest UI configuration (M=28.55s) followed by the large display (M=33.26s, 16% slower) and the hybrid (M=39.145s, 37% slower). Post-hoc tests corrected for multiple comparisons (Tukey's HSD) showed statistically significant differences between the hybrid (the slowest) and the other configurations, but not between the mobile and the large display. Figure 5.9 shows a summary of the mean completion time data while Figure 5.10 shows the scatterplot of completion times, with different UI configurations and data for the text task.

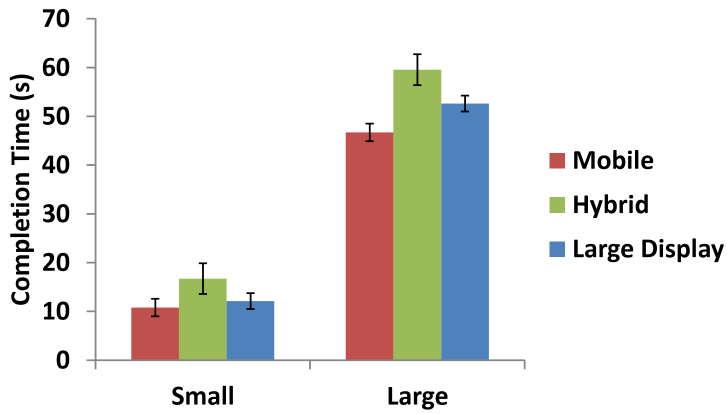


Figure 5.9: Text search: mean completion times with different UI configurations and data sizes. Error bars indicate 95% confidence intervals.

Error data was again analysed using a Friedman test, which showed no statistically significant differences between configurations (χ^2(2)=3.95, p=0.14). On average, the number of trials with errors was lowest in the hybrid (M=2%) followed by the mobile (M=4%) and the large display (M=6%).

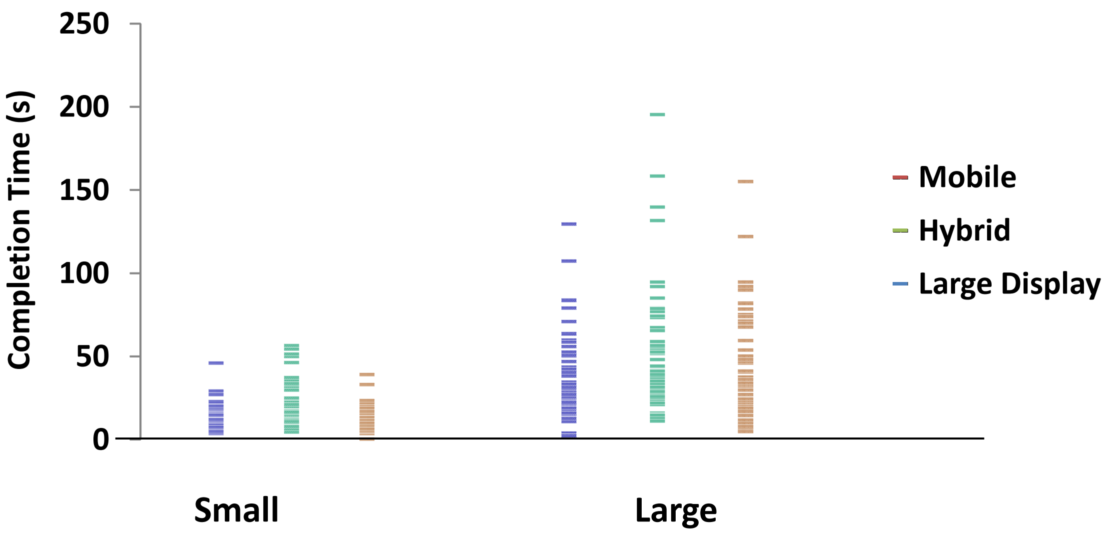


Figure 5.10: Text search: completion times with different UI configurations and data sizes.

Subjective Evaluation

Responses to the questions were analysed separately using a Friedman test. In this task we only found differences in performance ($\chi^2(2)$=6.21, p<0.05) as shown in Table 5.3.

Table 5.3: Text search: average ratings and statistics in the TLX questions.

Factor	χ^2**(2)**	**p**	**Mobile**	**Hybrid**	**Large Display**
Physical Demand	4.48	0.11	4.14	4.39	3.71
Mental Demand	4.73	0.09	2.75	3.25	2.66
Temporal Demand	4.45	0.11	3.86	3.68	2.98
Performance	6.21	<0.05	8.34	7.45	8.41
Effort	4.86	0.09	4.34	4.43	3.66
Frustration	1.69	0.43	3.07	3.18	2.64

In the overall ranking, the hybrid was the least preferred configuration (14 out of 22 participants, 64%). The large display was the most preferred (12 out of 22; 54%) followed by the mobile configuration (8 out of 22; 36%). A Friedman test of the rankings shows significant differences between the three configurations ($\chi^2(2)$=9.82, p<0.01). The complete preference choices are shown in Table 5.4.

Table 5.4: Text search: configuration preference rankings.

Configuration	Best	Middle	Worst
Mobile	8	10	4
Hybrid	2	6	14
Large Display	12	6	4

Most participants commented that they found it easier to scan text on the large display, although some preferred the mobile display for this task because they were not accustomed to reading on large screens. In general, participants said that they found themselves shifting attention between displays in the hybrid configuration, even though they realised that it did not help them. Note that participants were explicitly told at the beginning of these trials to make use of either or both displays as they pleased.

Auxiliary Analyses

An omnibus ANOVA of the length of interaction with configuration and data size as the main factors, and the participant as a random factor, yielded the main effects of data size ($F_{1,21}$=25.31, p<0.001, η_p^2=0.55), and configuration ($F_{2,42}$=23.24, p<0.001, η_p^2=0.52), as well as an interaction between the two ($F_{2,42}$=16.39, p<0.001, η_p^2=0.44). A post-hoc analysis (Tukey's HSD) showed statistical differences in the interaction length (in pixels) between the large display (M$_{small}$=2947px, M$_{large}$=24815px) and the other configurations (mobile: M$_{small}$=16px, M$_{large}$=1921px; hybrid: M$_{small}$=12px, M$_{large}$=1973px), but not between the mobile and the hybrid configurations. Figure 5.11 shows the length of interaction with different UI configurations and data sizes for the text search.

The regression between gaze shifts and completion time was not significant in both small ($F_{1,21}$=0.15, p=0.79) and large ($F_{1,21}$=0.00, p=0.99) data.

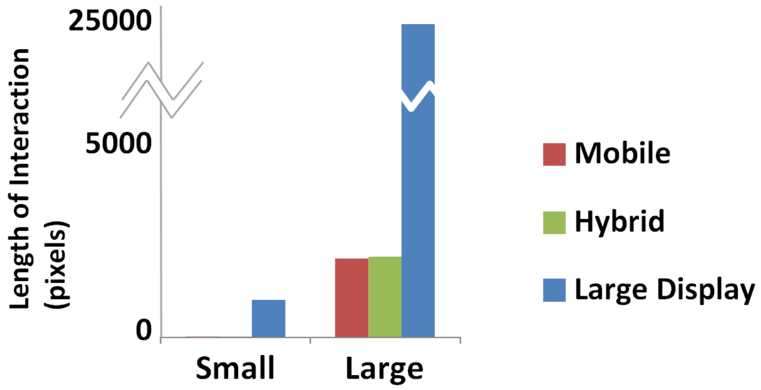


Figure 5.11: Text search: length of interaction with different UI configurations and data sizes. Hybrid and mobile length of interaction (LI) for small data are too small to be visible.

Summary

In the text search, the UI configuration had a large impact on task performance; the mobile and the large display were equivalent (thus confirming H1 and H6) and the hybrid performed the worst, regardless of whether the data fitted the mobile screen (thus confirming H2) or not (thus confirming H7). Although we did not find statistical evidence of a relationship between gaze shifts and the completion time, we can only attribute the poorer performance of the hybrid condition to the availability of two possible foci of attention, regardless of the number of gaze shifts performed. Note that the length of interaction does not match the completion time results; even though length of interaction was at least an order of magnitude larger for the large display configuration, completion times were still equivalent to those for the mobile configuration, and 15% faster than for the hybrid configuration. The problems of the hybrid technique were reflected in the overall ranking of the techniques by the participants. The tie in performance between the mobile and the large display is solved in favour of the latter, using the subjective data.

5.5 Experiment: Photo Search

The task for the photo search experiment is analogous to the text search task but using photographs of faces. It is representative of tasks that involve finding photos in a collection [200] and this has been tested in other experiments [81, 170]. Face images are increasingly being used as the visual representation of the user in social media (e.g., Twitter [244], Facebook [66]) and as avatars in virtual worlds (e.g., Second Life [213]). We included face photos of celebrities in this task because they are easier to identify, hence they provide a consistent dataset with respect to the complexity of visual search and make it easier to compare task performance across different UI configurations. The pilot tests showed that it was more difficult and time-consuming to identify the face images of unknown people. Since we were particularly interested in investigating the differences among UI configurations for the photo search, we tried to mitigate any possible variances among participants due to the difficulty of the task per se. Hence, we decided to include celebrities' face images for this task.

A photo of a famous Hollywood female celebrity was displayed at the top of the interface. The participants had to find and tap on images of the same person that appeared among photos of other celebrities. The photos were arranged on 3x6 grids per page (see Figure 5.12). In each trial participants had to find a different person. All photos shown were different, although some represented the same person (e.g., the photos for the correct answer). Each photo had 106x159px and measured 7.8x5cm on the large display and 1.8x1.2cm on the mobile device.

Under the small data condition, a single photo had to be selected among those in a 3x6 grid. For the large data, there were three correct answers among the photos on three 3x6 grids. Paging and input were identical to those in the text search experiment.

Figure 5.12: Photo search task on mobile and large display.

5.5.1 Hypotheses

We expected Hypotheses H1 and H2 as described in Section 5.3.1, and H6 and H7 described in Section 5.4.1 , also to be valid for the photo search task. We expected H6 to be valid for the photo search because eye fixation duration is longer while viewing face images [87] and the discrimination among facial features required for this task leads to shrinking of UFOV (see Section 2.5.5). Therefore, we did not expect any significant advantage in performance due to the wider visual field offered by the large display in this task.

5.5.2 Results

In this experiment we excluded the data from six participants according to the a priori criteria.

Performance

An omnibus ANOVA with configuration and data size as the main factors and the participant as a random factor revealed a strong effect on completion time of configuration ($F_{2,38}$=4.29, p<0.05, η_p^2=0.18), and data size ($F_{1,19}$=933.58, p<0.001, η_p^2=0.98), as well as interaction between the two main factors ($F_{2,38}$=7.71, p<0.001, η_p^2=0.29). To follow up the interaction, we performed separate analyses of trials under the large and small data conditions.

An ANOVA test on the small data trial results showed that configuration did not have any significant effect on completion time ($F_{2,38}$=2.91, p=0.09, η_p^2=0.13). Under the small data condition, the hybrid was the fastest configuration (M=8.89s), followed by the large display (M=10.35s, 16% slower) and the mobile (M=12.01s, 35% slower).

An ANOVA test of the large data trial results showed that configuration had a significant effect on completion time ($F_{2,38}$=12.33, p<0.01, η_p^2=0.39). Under the large data condition, the large display was the fastest configuration (M=33.68s), followed by the mobile (M=37.19s, 10.4% slower) and the hybrid (M=48.47s, 44% slower). Post-hoc tests corrected for multiple comparisons (Tukey's HSD) showed statistically significant differences between the hybrid (the slowest) and the other configurations, but not between the mobile and the large display. Figure 5.13 shows a summary of the mean completion time data while Figure 5.14 shows the scatterplot of completion times, with different UI configurations and data sizes for the photo task.

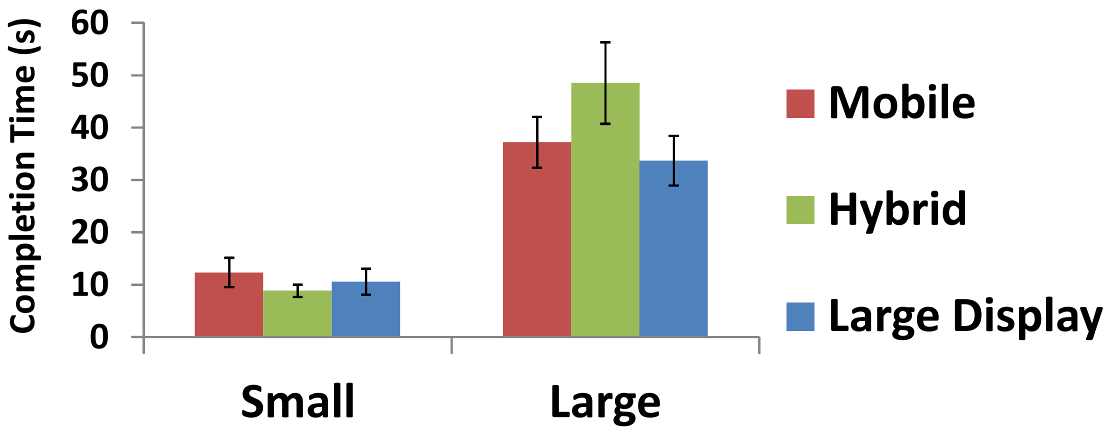


Figure 5.13: Photo search: mean completion times with different UI configurations and data sizes. Error bars indicate 95% confidence interval.

The error data was strongly non-parametric and was analysed using a Friedman test, which showed no significant differences between configurations (χ^2(2)=1.73, p=0.42). On average, the number of trials with errors was lowest in the hybrid (31%) followed by the large display (32%) and mobile (36%) configurations.

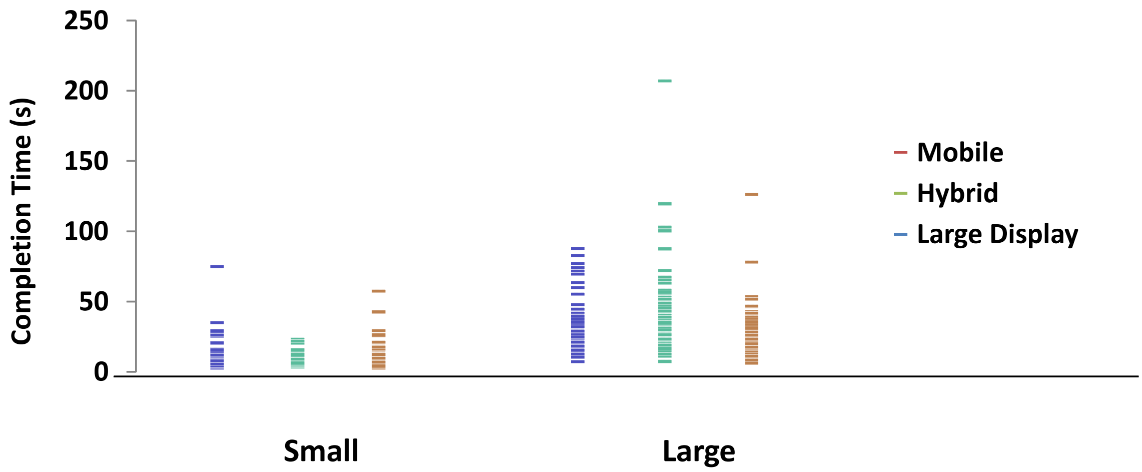


Figure 5.14: Photo search: completion times with different UI configurations and data sizes.

Subjective Evaluation

We found significant differences among the UI configurations with respect to physical demand ($\chi^2(2)$=9.08, p<0.05) and mental demand ($\chi^2(2)$=7.25, p<0.05). These results, along with the mean values of these ratings for different configurations, are shown in Table 5.5.

Table 5.5: Photo search: average ratings and statistics in the TLX questions.

Factor	χ^2**(2)**	**p**	**Mobile**	**Hybrid**	**Large Display**
Physical Demand	9.08	<0.05	5.03	4.85	3.9
Mental Demand	7.25	<0.05	1.8	2.22	1.45
Temporal Demand	4.95	0.08	3.85	3.37	3.18
Performance	4.82	0.09	6.12	6.68	7.18
Effort	4.35	0.11	4.5	3.9	3.25
Frustration	0.95	0.62	2.93	2.38	2.92

For the photo search, participants ranked the large display as best (13/20, 65%) and ranked the mobile as worst (10/20, 50%). The ranking scores are shown in Table 5.6.

Table 5.6: Photo search: configuration preference rankings.

Configuration	Best	Middle	Worst
Mobile	4	6	10
Hybrid	3	9	8
Large Display	13	5	2

Auxiliary Analyses

An omnibus ANOVA of length of interaction with configuration and data size as the main factors and the participant as a random factor yielded the significant effects of the data size ($F_{1,19}$=101.49, p<0.001, η_p^2=0.84) and configuration ($F_{2,38}$=28.51, p<0.001, η_p^2=0.60), as well as an interaction between the two ($F_{2,38}$=21.47, p<0.001, η_p^2=0.53). A post-hoc analysis (Tukey's HSD) showed statistical differences in the interaction length between the large display (M_{small}=872px, M_{large}=4217px) and the other configurations (mobile: M_{small}=11px, M_{large}=1115px; hybrid: M_{small}=14px, M_{large}=1132px), but not between the mobile and the hybrid configuration. Figure 5.15 shows the mean length of interaction with small and large data.

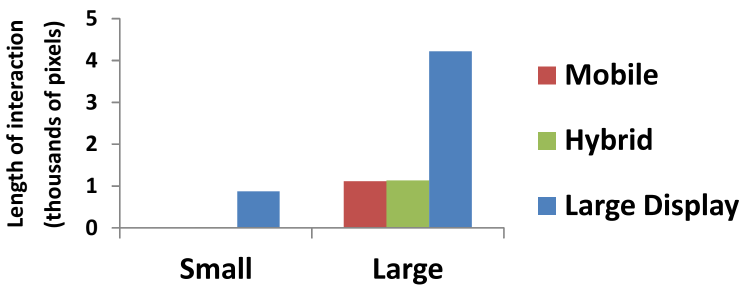


Figure 5.15: Photo search: length of interaction with different UI configurations and data sizes. Hybrid and mobile length of interaction (LI) for small data are too small to be visible.

To investigate the relationship between gaze shifts and the completion time, we ran a linear regression test for the data in the hybrid mode which was not significant in both the small ($F_{1,19}$=2.34, p=0.14) and large ($F_{1,19}$=1.59, p=0.22) data.

Summary

In the photo search task, the mobile and the large display performed equally well under the small (thus confirming H1) and large (thus confirming H6) data conditions, despite the large differences in interaction length. The large data condition brought out the differences in performance between techniques, which clearly showed that the hybrid is the worst option for both small (thus confirming H2) and large (thus confirming H7) data. Paradoxically, the mobile configuration was rated by participants as inferior to the hybrid configuration for all subjective workload questions, and it ranked very similarly as well.

5.6 Discussion

5.6.1 Distributing visual output across displays has a cost

In principle, the hybrid configuration allows people to take advantage of two very different displays, which could allow users to make the most of both for different aspects of the task at hand. For example, a user may employ the large display to gain an overview of the data space (which also enables physical navigation [11]), and the mobile display which allows direct input and a more flexible positioning of the device (e.g., bringing the display closer to the eyes) is beneficial [34]. However, here the experimental results indicate that distributing visual output incurs significant performance overheads: the hybrid configuration showed the worst performance in the text and photo search tasks and was equivalent to the worst performance in the map search task. We now explore several factors which might explain this disadvantage, including attention shift, visual/input space mismatch and distraction.

Cross-Display Switches

In general, a user can only look at one display at a time. Cross-display switching requires gaze shifts which force the user to quickly adapt to a display that is at a different distance, can show a different amount of visual information simultaneously (i.e., due to different resolution), and where visual objects are shown at a different size (i.e., due to different pixel density). Moreover, the visual content represented on the mobile display is often a subset of what a large display can show (with a large data). Typically, this requires a user to reorient themselves within the new visual space after a transition, i.e., to find what they were looking at in the previous display. The necessary mapping operation between the two visual representations might have an added cognitive cost. We were able to observe a direct relationship between the number of gaze shifts and the completion time for the map task, which suggests that each shift can cost an average of 1.8 ± 1.4 seconds with the small data, and 1.8 ± 0.96 seconds with the large data for this specific task and context. Smaller (but comparable) time costs are shown for a lower-level cross-display widget selection task (0.58 seconds reported in [181] and further analysed to be 0.64 ± 0.36 seconds) and for switching attention between a wall poster and a mobile device (0.36 seconds) [99].

One part of the switching cost might stem from the additional cognitive effort involved in deciding whether and when to switch displays. Designers of multi-display applications to support particular tasks should carefully consider such inherent attention shift costs versus the projected interaction design benefits.

Visual/input space mismatch

The eye can move much more quickly compared with other parts of the body and target acquisition usually requires the user to look at the target first, before actuating cursor control [110, 252]. Because the two displays show different views of the same information space, a mismatch can arise between the region being looked at on the large display and the information simultaneously visible on the mobile display. Since input is only available on the mobile device, once users locate the appropriate element on the large display they need to explicitly align their mobile view of the information with the focus of attention on the large display. In other words, there is a duplication of the navigation task: physical navigation with body, head and eye movement; and virtual navigation through explicit interaction. We observed instances of this behaviour in the video recordings, and three participants explicitly commented on it. Researchers and designers considering this configuration should develop and employ techniques to aid the user in better aligning their mobile view with their locus of attention on the large display.

Distraction

It is also possible that the mere presence of a large display, sometimes with moving elements (the scope window frame) is a source of distraction that users cannot avoid looking at. This would explain why most participants used both displays in the hybrid configuration even when the data also fitted the mobile display (i.e., small data condition), and even though the task performance was poorer. This suggests the design of multi-display applications needs to take into account the overall distraction factor versus the scope for improved interaction within and across tasks.

These experiments were not designed to tease out which of these cost elements is dominant in explaining the poorer performance of the hybrid configurations across all tasks. However, they helped identify possible culprits, and provide solid evidence that, for these tasks, the overheads introduced by the availability of two sources of visual output outweigh any advantages of having dual views.

5.6.2 Tasks and UI Configurations

The primary goal of these experiments was to investigate which UI configurations are best for which tasks. The large display configuration was best or equivalent to best in all tasks and data sizes. The mobile-only configuration was worst in the map task and equivalent to best in the photo and text tasks. These results also help clarify the role of interaction in the distribution of the interface; although the separation of input and output has been extensively studied as a factor influencing performance, we found that considerable differences in the amount of interaction for the photo and text tasks did not impact on the corresponding completion time differences. The large display configuration required amounts of interaction that were orders of magnitude above those in the mobile and hybrid configurations but still performed best or equivalent to best. This suggests that for tasks that do not require continuous navigation such as photo and text search, how we distribute visual information across displays is more relevant than the directness of the interface (i.e., direct vs. indirect input).

Surprisingly, the hybrid configuration was ranked more favourably by participants than indicated by its performance or their own subjective workload ratings; the hybrid configuration was clearly ranked worst in the text task, but it came close second in the map task and was second in the photo task, even though its performance was substantially inferior to that of the mobile. Although this anomaly requires further study, we speculate that users may like the freedom of choosing which display to use, regardless of performance.

5.6.3 Large display indirect vs. small display direct

Our results also provide a valuable comparison between the mobile and large display configurations. The large display was, on average, ranked above the mobile in all three tasks, and participants consistently rated it as performing better and being less demanding across all 18 Likert scales. There are various possible explanations for these results. First, it is better to have more simultaneous pixels without the need to interactively manipulate the viewport. This concurs with results from previous studies on vertical large displays [11], and suggests that eye/head/body navigation is superior to interactive navigation. This is not merely a resolution issue: our maps, texts and photos all had the same resolution and layout regardless of the configuration.

Second, it is possible that for a given fixed amount of visual information people prefer to interact with larger objects. Third, people might prefer the large display because it is more stable, and does not require looking down or holding the device at a certain angle or distance. Fourth, it might be due to the natural human attraction towards larger objects [216].

Importantly, we found no evidence suggesting that the loss of "directness" between input and output is important in the discussed scenario, or that the ability of users to place the visual output of a mobile device anywhere in their visual field is beneficial for completing these tasks.

5.6.4 Limitations

Although these experiments cover a broad range of tasks that are common in mobile situations, there are other tasks such as text composition, photo manipulation or web browsing that might be affected differently when using the various UI configurations. Exploration of these tasks would be valuable in order to expand and complete these results. Due to the limited nature of our experimental design, we only tested two levels of data size; further experiments with data that require viewport changes on a large display should be valuable in improving the understanding of how to support interaction with *very large* data in mobile multi-display situations.

The UI configurations chosen are representative of the single and multi-display options that are already feasible in many scenarios (e.g., wherever there is a large public display and a communication channel between the mobile and the large display devices). However, by excluding configurations that require input sensing in the environment, we were constrained to arrangements that are readily workable with widely installed infrastructures. Other alternatives such as direct touch on the large display [153], visualization of off-screen locations on the mobile display [38] or more sophisticated combinations of small and large display content [34] fall beyond the scope of this research and need to be addressed in the future. Although we did not explicitly consider the use of mobile projected large displays (e.g., [81, 91]) we believe that the results from our study provide valuable guidance to the effects different UI configurations might have on future mobile projector-based systems.

As explained in Section 5.2.4, we used opportunity sampling to recruit our participants. The participants were in the age group of 19–33; all of them had normal or corrected-to-normal vision, and most of them were familiar with the use of smartphones and large displays. The same experiments carried out with elderly people or people with near-sighted or far-sighted vision, might give rise to different results with the different UI configurations.

The experimental results are likely to vary depending on the size and resolution (i.e., elements identified as *how much* characteristics in Section 2.5.7) of the displays involved. For instance, we assume that in our experimental setting, a greater difference in the resolution of the mobile device and the large display would cause a larger mismatch in the visual/input space (as discussed above in Section 5.6.1), and that would adversely affect task performance in the hybrid configuration to a greater degree. On the other hand, increasing the resolution of the large display while keeping its size unchanged would make the visual objects appear relatively smaller (due to increased pixel density) and that might require the users to move closer to the large display to see them clearly. It would also be interesting to investigate the situations where the information space becomes too large to be simultaneously visible on the large display and virtual navigation (see Section 2.5.9) on the large display is required to see all the information.

Finally, our choice of controlled laboratory studies as a methodology is adequate for studying tasks at this level; however, to learn more about the value of these UI configurations in naturalistic settings, further research is necessary that would require a mix of quantitative and qualitative methodologies in less controlled situations.

5.6.5 Lessons for Practitioners

This study provides useful evidence for the design of mobile and multi-display distributed user interfaces:

- Large displays can be used in mobile tasks to enhance task performance, reduce subjective workload, and increase user preference.
- Distributing the visual output in the “cloned” category (i.e., the small data condition)

and “partial/total” sub-category (i.e., the large data condition) of the “coordinated” category of content coordination (see Section 3.2.3) across “visual field & depth discontiguous” (see Section 3.2.1) displays with “field-wide” angular coverage should be avoided for visual search tasks.

- Tasks that require continuous navigation of the data space (e.g., a map search) and make use of the peripheral vision benefit most from the addition of a large display.

5.7 Conclusion

Supplementing a mobile device with large displays in the environment has been widely considered as an opportunity to overcome some of the limitations of small mobile displays. However, there is very little evidence to guide designers on how cross-display switching in different distributions of user interfaces affects task performance in these cases. In this chapter, we report on a user study that provides empirical evidence of how “no-attention-switch” and “attention-switch” configurations of input/output across a mobile device and a large vertical display affect task performance, subjective workload and preferences in visual search tasks. The experimental results show that the “no-attention-switch” UI configurations are generally the best option for visual search tasks, i.e., the mobile-controlled large display is the best followed by the mobile-only configuration. Subjectively the participants preferred the mobile-controlled large display to other configurations except in the map search task where it ranked equal with the hybrid configuration. Although we observed that the “attention-switch” configuration with distributed visual content was worst, or equal to worst, in visual search tasks, participants seemed to prefer it in many cases to the mobile-only single-display baseline. The time cost of switching attention across a handheld mobile device and a vertical large display in the map search task has been calculated to be $1.8{\pm}1.4$ seconds with the small data (i.e., the data simultaneously visible on the mobile display), and $1.8{\pm}0.96$ seconds with the large data (i.e., the data simultaneously visible on the large display). We have also suggested several sources of overheads derived from splitting the interface across different displays, backed by empirical evidence, and provided advice for practitioners on how to apply these findings in the design of the next generation of multi-display user interfaces.

If you thought that science was certain—well, that is just an error on your part.

Richard Feynman

Chapter 6

Conclusion and Future Work

This chapter provides a conclusion for the current work and points to the directions for future research. It summarises the discussion of the taxonomy of Multi Display User Interfaces (MDUIs) presented in Chapter 3, and the user studies explained in Chapters 4 and 5. Starting with an overview of the objectives of this research in Section 6.1, the findings of the experiments are summed up in Section 6.2, followed by a description of the contributions of this thesis in Section 6.3. The scope and limitations of the current work are then considered, and directions for future research discussed, in Section 6.4. Section 6.5 concludes the chapter.

6.1 Research Objectives

This research has attempted to enhance our knowledge of the factors that affect cross-display attention switching in a multi-display user interface, and the overhead induced by cross-display switching during user interaction with a handheld mobile device and a vertical large display. The main problem this work has attempted to address is:

How does switching of visual attention between a handheld mobile display and a vertical large display affect a single user's task performance during mobile interaction

with large displays?

We have tried to address this problem through empirical comparison of task performance in multiple widget selection and visual search tasks with “no-attention-switch” as well as “attention-switch” configurations of UI elements across a mobile device and a large display. We broke down the main problem statement into three questions as follows:

- *Question 1*. In a task involving selection of multiple widgets in sequence, what is the comparative performance of “no-attention-switch” (widgets on the large display) and “attention-switch” (widgets replicated on the mobile device as well as on the large display) UI configurations?
- *Question 2*. In a task involving a visual search of map, text and photo, what is the comparative performance of “no-attention-switch” (mobile-only, mobile-controlled-large-display) and “attention-switch” (hybrid) UI configurations?
- *Question 3*. What is the quantitative value of the overhead caused by the cross-display attention switching in multiple widget selection and visual search tasks?

6.2 Summary of Experimental Results

This section is organised such that the questions posed in Section 6.1 are answered with reference to the experimental results described in different chapters of this thesis.

Answer to Question 1: Chapter 4 presents an empirical analysis of task performance when selecting multiple widgets under a “no-attention-switch” vs. that under an “attention switch” UI configuration. The “no-attention-switch” configuration was exemplified by the Distal Selection (DS) technique that uses a mobile pointer to zoom-in to the region of interest and select widgets on the large display. The “attention-switch” configuration was exemplified by the Proximal Selection (PS) technique that involves pointing at the large display and transferring the zoom-in view of the selected region onto the mobile touchscreen for selection thereafter.

Experimental results show that PS takes less completion time than DS as the number of widgets increase. In terms of the subjective workload, we found a significant difference between these techniques for the physical effort involved; PS fared better than DS in this matter. The user preference was overwhelmingly in favour of PS over DS. This shows that for a task involving selection of multiple widgets in sequence, the advantages of PS outweigh the cost of initial cross-display switching as the difficulty level of the task (i.e., the number of widgets to select) increases.

Answer to Question 2: Chapter 5 reports on a user study that provides empirical evidence of how "no-attention-switch" and "attention-switch" configurations of input/output across the mobile and large display affects task performance, subjective workload and preferences in visual search tasks with map, text and photo. The experimental results show that the "no-attention-switch" configuration is generally the best option for visual search tasks i.e., the mobile-controlled large display being the best, followed by the mobile-only configuration.

Although it was observed that the "attention-switch" configuration was worst or equal to worst for all visual search tasks, participants seemed to prefer it in many cases to the mobile-only single-display baseline.

Answer to Question 3: In Chapter 4, we calculated using our experimental data that the overhead in terms of the time taken for cross-display attention switching in a multiple widget selection task across the mobile device and large display was 0.64 ± 0.36 seconds. In Chapter 5, we calculated the time cost of cross-display switching in a map search task to be 1.8 ± 1.4 seconds with the data simultaneously visible on the mobile display; 1.8 ± 0.96 seconds with the data simultaneously visible on the large display.

6.3 Contributions of Thesis

To sum up, this thesis makes the following contributions to the literature.

6.3.1 Taxonomy of Multi-Display User Interfaces (MDUI)

This thesis introduces a taxonomy based on the factors associated with the visual arrangement of MDUIs that can influence visual attention switching while interacting across displays (see Section 3.2). These factors are as follows:

- *Display Contiguity*. This refers to the way multiple displays appear contiguous in the visual field or lie at the same distance from the observer.
- *Angular Coverage*. This refers to the angular size of the multi-display ecosystem containing MDUIs.
- *Content Coordination*. This refers to the coordination among the visual contents shown across displays containing MDUIs.
- *Input Directness*. This refers to the input mechanism supported in the system containing MDUIs.
- *Input-Display Correspondence*. This refers to the way the input mechanism manipulates visual output across displays containing MDUIs.

Using this taxonomy, the "attention switch" UI configurations of experimental prototypes discussed in Chapter 4 and Chapter 5 of this thesis are classified as *visual field & depth discontinguous*, *field-wide*, *cloned* (in Chapter 4, and the small data condition in Chapter 5) as well as *coordinated* (in the large data condition of Chapter 5), *hybrid*, and *redirectional*.

6.3.2 Analysis of Cross-Display Switching for Multiple Widget Selection

We provide empirical evidence of how the effect of cross-display switching on task performance, subjective workload and preferences in the selection of multiple widgets changes with respect to the changing difficulty level of the task (i.e., an increasing number of widgets to select) [181]. The experimental results presented in Chapter 3 suggest there is no significant difference in completion time for selecting two widgets between the "no-attention-switch" (i.e., widgets on the large display) and "attention-switch" (i.e., widgets replicated on the mobile device as well as on the large display) UI configurations. However, as the number of widgets increases, the completion time is significantly reduced using the "attention-switch" UI configuration, despite the overhead of initial cross-display attention switching.

6.3.3 Analysis of Cross-Display Switching for Visual Search

We provide an empirical analysis of how different "no-attention-switch" (mobile-only and mobile-controlled large display) and "attention-switch" (hybrid) configurations of input/output across the mobile and large display affect task performance, subjective workload and subjective preferences in the visual search of map, text and photo [183]. Experimental results show that a hybrid configuration where visual output is distributed across displays is worst or equivalent to worst in visual search tasks. A mobile device-controlled large display configuration performed best in the map search task, and equal to best in the text and photo search tasks (tied with a mobile-only configuration).

6.3.4 Lessons for Practitioners

Based on the experimental results described in Chapter 4 and Chapter 5, we provide lessons for designers of MDUIs as follows:

- Direct pointing under the "no-attention switch" UI configuration (as exemplified in the DS technique) is faster for selecting widgets on the large display if there are two widgets to be selected in series.
- With an increasing number of widgets to be selected (e.g., in tasks involving mul-

tiple item selection) on the large display, the faster performance of the PS technique outweighs the cost of initial cross-display attention switching associated with this technique.

- Moving the user interaction from the large display to the mobile device should save the user considerably more than 0.64 ± 0.36 seconds (i.e., the time cost of cross-display switching in a multiple widget selection task), otherwise interaction is better being done on the large display.
- Distributing the visual output in the "cloned" (i.e., small data condition in Chapter 5) and "partial/total" sub-category (i.e., large data condition in Chapter 5) of the "coordinated" category of content coordination (see Section 3.2.3) across "visual field & depth discontiguous" (see Section 3.2.1) displays with "field-wide" angular coverage (see Section 3.2.2), should be avoided for visual search tasks. In the map search task, the cost per cross-display switch is 1.8 ± 1.4 seconds with the data simultaneously visible on the mobile display, and 1.8 ± 0.96 seconds with the data simultaneously visible on the large display.
- Tasks that require continuous navigation of the data space (e.g., a map search) and that make use of peripheral vision will benefit most from the addition of a large display.
- The mobile and the large display show no significant difference in the task performance for the visual scanning of informational texts and face photos, i.e., tasks that require detailed discrimination and do not rely much on peripheral vision. Hence, searching text and face photos on the mobile device is as efficient as doing it on the large display.

6.3.5 Minor Contributions

As minor contributions, this thesis provides an estimation of the overhead in terms of the time taken in switching attention between a handheld mobile device and a vertical large display. For the widget selection task, the time cost of cross-display switching is about $0.64{\pm}0.36$ seconds; for the map search task, this cost is about $1.8{\pm}1.4$ seconds with the data simultaneously visible on the mobile display, and $1.8{\pm}0.96$ seconds with the data simultaneously visible on the large display. These results indicate that cross-display switching causes a higher overhead with the higher cognitive demand of the latter task.

6.4 Limitations and Future Work

The research presented in this thesis is focused on the single-user interaction of a handheld mobile device with a vertical large display. We have tried to identify the overhead of cross-display attention switching due to the visual arrangement of UI elements in systems containing MDUIs. We have tested different experimental conditions in tasks involving multiple widget selection, and visual search of text, photo and map content; all these tasks made use of the mobile input while the output was shown on either the mobile device or the large display. In this section, we discuss the limitations of our experimental approaches and analyses, and highlight the directions for future work.

6.4.1 Input Mechanisms

In the experiments described in Chapter 4 and Chapter 5 of this thesis, the "attention-switch" UI configurations we tested are classified as *hybrid* and *redirectional* in terms of *input directness* and *input-display correspondence* respectively, according to the taxonomy presented in Chapter 3.

It would be interesting to explore how different permutations of input directness and input-display correspondence affect cross-display attention switching and performance differences induced by these differences. Of particular interest is the change of input-display correspondence as interactive large displays increasingly find their way into everyday life. In an impending situation where multi-touch screens become the norm and the users are able to touch the interface both on the handheld device and the external display, selecting which screen to choose for interaction would require an additional cognitive effort and attention switching. Examples may include interacting with the "PixelSense" interface of Microsoft Surface 2.0 using a personal handheld touch-device.

To date, experiments have been undertaken with the input provided using a mobile camera [14], mobile accelerometer [35], mobile ray-pointing [115, 152, 181], mobile keyboard and joystick [160]. Some other input devices used for large display interaction are Nintendo Wii™ Remote Control and Nintendo Wii™ U.

However, multiple sensing devices are currently installed in the environment (e.g., cameras, presence detectors) that could be used to provide context-aware input for interaction across multiple displays. Some work is already under way in this direction, such as the Digital Vision Touch (DViT) system [147] that uses cameras to determine where a person touches a large display. Researchers are experimenting with *hands-free* gaze and speech input in Attentive User Interfaces [136] and tackling the voice menu navigation problem with cross-device user experience integration [271]. Kaptelinin and Whlen [122] present an interface technique named VAVS ("voice-assisted visual search") that employs user's voice input to assist the user in searching for objects of interest in complex displays. The advent of a motion sensor and body recognition system in Microsoft Kinect™ offers new opportunities for gesture-based and "in the air" interaction with MDUIs.

6.4.2 Tasks

This work has considered widget selection and visual search tasks to explore the performance effects of attention switching across a handheld mobile device and a vertical large display. It remains to be seen how attention switching affects task performance with MDUIs in complex cognitive tasks such as information comprehension and sense-making [6]. Studies of the users of multi-monitor computers [85] and virtual desktops [197] have shown the users to demarcate the screen space with respect to primary and peripheral tasks.

It would be interesting to study how users distribute their primary and peripheral tasks across displays in a mobile multi-display environment in different contexts.

Studies have found advantages in using large displays in spatial tasks [183, 231, 232] because they provide a wider visual field that helps the users make use of peripheral vision, physical navigation and embodied interaction [12]. However, tasks that require detailed discrimination have not performed better on large displays, such as reading comprehension [232], and text and photo search tasks [183]. Any future task model for MDUIs might also take into account the nature of the tasks and the capabilities of the interacting displays so that the distribution of the UI across displays of varying sizes and resolutions leads to better task performance.

The theory of *distributed cognition* [98] suggests that cognitive processes may involve coordination between one's mental abilities and the external material world. It remains to be explored how this theory helps us in understanding the ways different visual arrangements of UI elements in an MDUI may affect the performance of complex cognitive tasks.

6.4.3 Modality of Feedback

The experiments described in this thesis provided feedback regarding user interaction in a single-modality visual format. How the provision of feedback in different modalities affects task performance in MDUIs remains to be explored. The experimental evidence shows that instructional materials that use dual-mode presentation techniques (e.g., auditory text and visual diagrams) can result in superior learning compared to equivalent, single-modality formats (e.g., visual text and visual diagrams) [241]. Walker and Brewster [247] presented a spatialised audio progress bar in a mobile device and found that it improved task performance over that of a conventional visual progress bar. The provision of audio-haptic feedback [36, 42] in mobile devices may facilitate "eyes-free" and "heads-up" interaction and mitigate the reasons for switching attention.

6.4.4 Visual Arrangements of Output

Under the experimental conditions presented in this thesis, the mobile device either replicated the content on the large display (discussed in Chapter 4) or showed a partial view of it (discussed in Chapter 5). According to the factors listed in our taxonomy of MDUIs, these conditions fall into the *cloned* (i.e., in Chapter 4, and small data condition in Chapter 5) and "partial/total" sub-category of *coordinated* (i.e., large data condition in Chapter 5) categories of content coordination with *field-wide* angular coverage and *visual field & depth discontiguous*.

Although the display contiguity and angular coverage used in our experiments seem to be quite common among MDUIs we surveyed, the same cannot be said about our content coordination conditions. For instance, the "augmented" sub-category of *coordinated* category that is more common among MDUIs than the sub-category (i.e., "partial/total") we tested. Mobile devices can be used to show a detailed and personalised view of the publicly available content shown on a large display [199, 207]. Dual device interfaces have been used in interactive TV applications, such as using a mobile device to display translated foreign language terms in a TV programme [67], or helping users to select content in different programmes [40, 41]. In multi-player games, different screens show the public and private content on different devices, such as in Poker Surface when a player's private game plan is shown on a mobile device and the table display shows the public game play [215].

On the other hand, Grudin [85] observed that the typical division of visual space in a multi-monitor desktop computer consists of the contents of primary and peripheral tasks placed on separate displays. Similar task-based division of screen space was observed in a study of the "virtual desktop" users [197]. Moreover, in multi-display environments in offices [102] and meeting rooms [109, 260], screens exhibit different modes of collaboration among the audience. For example, the large display may show the shared public data, and the smaller portable display is reserved for private information. How different visual arrangements of UI elements in MDUIs affect attention switching and task performance in the aforementioned situations remains to be explored.

6.4.5 Multi-User Scenarios

The experiments in this research involved single-user interaction across a mobile device and a large display. Although it is increasingly common for an individual to interact across multiple displays simultaneously [15, 27, 199, 207], multiple displays also offer great potential for sharing information and collaboration among group members [57, 82, 109, 260]. Multi-player games provide another example of this situation [215]. Such arrangements are interesting because here it not just the individual interaction, but also the interaction of members of the audience with each other and with the displays, that may influence switching of attention across displays. Moreover, the issues of privacy and selective exposure of content become important in these cases, and the visual arrangement of UI elements also has to address these issues. It would be interesting to explore how multi-user collaboration can be facilitated with different visual arrangements of UI elements.

6.4.6 Hybrid Navigation Patterns

The experimental conditions under which we conducted our studies involved egocentric navigation in MDUIs and within this, we limited the scope of our research to eye and head movements in cross-display attention switching (see Section 2.7). In future work, cross-display switching due to different body movements ought to be studied. Moreover, attention switching due to exocentric and virtual navigation in MDUIs remains to be explored. Another interesting area to explore would be the combination of various navigation patterns in MDUIs, for example, the content on a display changing (virtual navigation) due to the movement of a user towards the display (egocentric navigation) or the movement of a display towards the user (exocentric navigation). In this regard, several researchers have considered the interaction of a spatially-aware mobile device with a large digital surface. For example, Chameleon [71] is a palmtop computer aware of its position and orientation and its contents would vary depending on its spatial orientation to the vertical display. Rekimoto's spatially-aware M-Pad is a handheld device that shows property information on a display object when the M-Pad is close enough to that object [190]. The Hello.Wall prototype [177] introduced the notion of distance-dependent semantics, where the distance from the wall defined the interactions offered and the kind of information shown on the wall. The Lean and Zoom [93] system detects a user's proximity to the display using a camera and markers, and magnifies the on-screen content proportionally, i.e., the smaller the distance, the larger the displayed content. Some other spatially-aware displays that change the display content based on the forward or backward movement of the user are presented in [16, 116, 245]. Most of the aforementioned experiments makes use of single display systems and it remains to be explored how the dynamic content changes in a multi-display environment due to different navigation patterns affect the user experience.

6.4.7 Computational Model of Attention Switching

In this thesis, we have provided an estimation of cross-display attention switching time for two tasks, i.e., multiple widget selection (0.64 ± 0.36 seconds) and a map search (1.8 ± 1.4 seconds with the data simultaneously visible on the mobile device, 1.8 ± 0.96 seconds with the data simultaneously visible on the large display). As explained earlier, this attention switching is manifested in up-and-down movements of the eye and the head while interacting across a mobile handheld device and a large vertical display. One interesting direction for the future exploration is to formulate mathematical equations for the attention switching time associated with different body movements (e.g., lateral head movements, changing posture). Moreover, the attention switching time associated with exocentric and virtual navigation patterns in MDUIs remain to be explored. In future work, we plan to conduct experiments under these conditions and explore a computational model of cross-display attention switching, similar to how Fitts's law [70] models manual movements towards a target region.

6.4.8 Next-Generation Operating Systems

At present, efforts to build MDUI-based applications are being led by application developers and UI designers. Already some tools for automatic user interface generation exist [161] and they might be extended to support "on the fly" design of UI elements distributed across multiple displays. However, in the future, it might become possible to provide support for MDUIs at the operating system level. This means that next-generation operating systems might be able to detect the presence of devices in the multi-display ecosystem, and distribute UI elements across different displays dynamically. Researchers have already introduced middleware and meta-operating systems for multiple heterogeneous devices such as 2K [126], iROS (Interactive Room Operating System) [111], BEACH [235], GAIA [202] and Aura [222]. Our current research on the performance effects of different visual arrangements of UI elements in MDUI might be a stepping stone towards supporting the creation of performance-optimal MDUIs in next-generation operating systems.

6.4.9 Participants

The participants in our experiments are in the age group 30–45 (in widget selection task) and 19–33 (in visual search tasks), with normal or corrected-to-normal vision. The educational and professional backgrounds of them mean they were mostly familiar with latest technologies. As a result, they represent a tiny sample of the general population. It remains to be explored how different configurations of MDUIs affect the task performance and user experience of elderly people or those with near-sighted or far-sighted vision. It would also be interesting to study how MDUIs are used by people from different walks of life such as schoolchildren, tourists, retail customers and knowledge workers.

6.4.10 Multi-displays in the Wild

Users of mobile devices are often in motion or outdoors when they use their devices (e.g., making/receiving calls, reading/sending text messages). Large displays are also increasingly being installed in outdoor places such as shopping malls, bus stations and airports. These observations suggest that there is a room for interaction between mobile and large displays in the wild [149]. Another interesting area is the mobile interaction with dashboard displays in cars, for instance in the Nokia Car mode application [178].

Previous field-based studies of mobile devices have identified significantly more problems with usability, interaction style and cognitive load than were identified in laboratory settings [162]. What kinds of user experience different visual arrangements of UI elements across MDUIs in the wild will bring forth, remains an open question.

6.5 Concluding Remarks

Users are increasingly shifting from using a single personal computer to interacting with a wider range of computing devices (e.g., laptops, tablets, smartphones, e-book readers). The proliferation of computing devices has created opportunities to make different applications and services readily accessible on multiple devices. The classical Graphical User Interface (GUI) model based on a "desktop metaphor" is increasingly becoming outdated as it fails to accommodate the user experience across multiple heterogeneous devices. Some solutions have been proposed to distribute UI elements across multiple devices. However, the literature to date has provided little information on how cross-display attention switching, due to the visual arrangement of UI elements across handheld devices and external displays, affect the task performance.

This thesis has attempted to explore the effects on performance due to switching visual attention across a handheld mobile display and a vertical large display during different tasks. Starting with a comprehensive review of relevant literature, we have introduced a taxonomy based on the factors associated with the visual arrangement of UI elements that can affect cross-display attention switching in Multi Display User Interfaces (MDUIs). We have provided an experimental investigation into how cross-display switching affects a single user's task performance, subjective workload and preference in multiple widget selection and visual search tasks. In addition to calculating the cost in time of cross-display switching in those tasks, we have outlined guidelines for designers of MDUIs. The thesis concludes by discussing some directions for future work that are aimed at improving task performance and generating better user experiences with MDUIs.

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