# Effects of Visual Separation and Physical Discontinuities when Distributing Information across Multiple Displays

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## Abstract

*Systems that include multiple integrated displays distributed throughout the working environment are becoming prevalent. Compared to traditional desktop displays, information presented on such systems is typically separated at much wider visual angles. Additionally, since displays are often placed at different depths or are framed by physical bezels, they introduce physical discontinuities in the presentation of information. In this paper, we describe a study that utilizes a divided attention paradigm to explore the effects of visual separation and physical discontinuities when distributing information across multiple displays. Results show reliable, though small, detrimental effects when information is separated within the visual field, but only when coupled with an offset in depth. Surprisingly, physical discontinuities such as monitor bezels and even separation in depth alone do not seem to affect performance on the set of tasks tested. Following the findings, we provide recommendations for the design of hardware and software in multiple display environments.*

## 1. Introduction

For years, multiple integrated displays have been used in environments that require multiple people to simultaneously monitor and interact with complex visual information. Such environments include control rooms, operations centers, trading floors, and planning rooms. Recently, there has been a trend in the marketplace towards similar multiple display systems in more traditional workspaces. In both cases, having multiple displays enlarges the physical display area, allowing the system to present information across much wider visual angles from the user. Also, since displays are often placed at different depths or are framed by physical bezels, physical discontinuities are introduced in the presentation of information in these workspaces. Yet, relatively little is known about how to best present information to the user given these display characteristics. In this paper, we describe a study designed to explore the effects of visual separation and physical discontinuities when distributing information across multiple displays.

In designing any study, we must consider internal validity and external validity. Internal validity refers to how well an experiment allows for causal interpretability of the results. This is usually best attained by carefully controlling all variables within an experiment, hence eliminating any alternate explanations to observed phenomena. Usually, this is done in a laboratory environment with somewhat contrived tasks. External validity, on the other hand, refers to how well results can be generalized. This is best attained in real world settings that are representative of environments in which results may be applied. In these settings, many factors are either difficult or impossible to control.

There is a constant tension between internal and external validity in experimental research, forcing a tradeoff in emphasis between the two. We have designed our study with a focus on internal validity, concerning ourselves mostly with systematically understanding the problems we are studying. However, in doing so, we have also maintained a sensitivity to external validity, ensuring that the tasks we have chosen are representative of real world tasks, and that generalizing these tasks remains a simple cognitive exercise.

To isolate and understand individual factors of interest in our work, we created a display system that allowed us to carefully control the separation and discontinuities associated with multiple displays. We ran a study that utilized a divided attention paradigm across several different display conditions. The test included a primary task, done in conjunction with a secondary or tertiary task. In the primary task, users had to proofread and identify grammatical errors within a set of text articles. While doing this, users also performed the secondary task, *notification detection*. In this task, users had to detect and act upon visual changes outside the focal region of the primary task. Upon detecting notifications, users performed the tertiary task, *text*

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*comparison*, in which they had to cross reference and compare content displayed in multiple locations on the displays. We picked these tasks to be representative of tasks information workers perform while multitasking in a single user desktop situation.

Results from the study demonstrated a reliable, but small, detrimental effect on performance from separating information within the visual field, but only when it is further separated by depth. We found that physical discontinuities introduced by bezels or depth alone had no effect of performance for our set of tasks. We conclude with design recommendations.

## 2. Related Work

### 2.1. Multiple Display Systems

Many researchers are building multiple display workplaces as well as designing interfaces that exploit affordances offered by these systems. For example, Raskar et al. (1998), in their *Office of the Future*, envision a workplace in which every surface serves as a high-resolution projected display. In their system, they modify images projected onto particular surfaces so that they appear correctly to observers at known locations.

Streitz et al. (1999) have also worked on integrating real architectural and virtual information spaces to create an environment they call *i-LAND*. They have populated this environment with various physical components, each with its own associated display device. Together these displays provide physical affordances that aid in content organization and work process control. Rekimoto & Saitoh (1999) have implemented a similar system, which they call *Augmented Surfaces*, but have focused on interaction techniques. In one technique, called hyperdragging, users utilize the physical relationship between devices to transfer information between them.

In *Kimura*, MacIntyre et al. (2001) utilize projected peripheral displays to support the perusal, manipulation, and awareness of background activities in order to manage multitasking between multiple ìworking contextsî. In a similar setup, Tan et al. (2001) use their *InfoCockpit* to improve human memory for information viewed. They not only use multiple monitors to spatially distribute information and engage human memory for location, but also present synthetically created visual context on large ambient projection displays to leverage human memory for place.

To further explore workplaces with multiple displays, Tan et al. (2003) created the *Display Garden*, a rapidly configurable collection of physical display devices. They have followed up their earlier work with studies showing that while reading comprehension was not affected by the physical size of displays, larger displays, even at constant visual angles, immerse users more and allow them to perform better on spatial orientation tasks.

Swaminathan & Sato (1997) summarize much of this work by describing three distinct multiple display configurations: (i) *distant-contiguous* configurations consist of multiple displays placed at a fairly large distance from the user so as to occupy the same visual angle as a standard desktop monitor; (ii) *desktop-contiguous* configurations consist of multiple displays placed at a distance equivalent to a standard desktop monitor so as to drastically widen the available visual angle; (iii) *non-contiguous* configurations consist of display surfaces at different distances from a user and that do not occupy a contiguous physical display space.

Most systems we have examined fall into the latter two categories. These systems share one characteristic: information is displayed across a wider visual field such that not everything is always contained in the foveal region. In fact, this is true even of many traditional desktop and distant-contiguous systems, since the typical visual angle of a display is 20-40 degrees, while foveal vision covers only about 2 degrees. In addition, non-contiguous configurations introduce physical discontinuities as information is separated at different depths or by physical objects. In our work, we explore the effects of visual separation and physical discontinuities when distributing information across multiple displays.

### 2.2. Human Vision and Peripheral Information

There has been a long history of work in psychology and psychophysics documenting the size and shape of the visual field. In their work, Carrasco & Naegele (1995) present the *eccentricity effect*, which shows that targets presented near the point of visual fixation are noticed much more easily than targets further away. Wolfe et al. (1998) present a summary of visual explanations of this effect as well as a new explanation claiming that attention is partially modulated by eccentricity, leading to higher activation and faster search times for nearer objects. Additionally, they show that these eccentricity effects are reduced when there are fewer distractions on the screen. Other researchers have shown that mental workloads greatly affect the size and shape of the visual field. For example, Rantanen & Goldberg (1999) show that heavier workloads not only shrink the visual field by up to 14%, but also cause it to be vertically shorter and horizontally elongated.

Researchers, aware of the capabilities of the human visual system, have designed various tools that leverage peripheral vision and attention. For example, Cadiz et al. (2002) provide a wide range of awareness information on the side of the display in their *Sidebar* system. In their work, they build upon previous research investigating methods of providing the most peripheral information while having the least impact on main task performance (Maglio & Campbell, 2000; McCrickard et al., 2001). Grudin (2001), in observing how users use multiple displays, asserted that the division of space afforded by multiple non-contiguous displays is sometimes beneficial over having a single contiguous space. He explains that the divisions created often help users segment the working space not only to ìpark objects out in the peripheryî but also to more effectively assign specific functions to each subspace. Given this assertion that the physical divisions seem to create separate mental subspaces, we expected the divisions to be a distraction and to add cognitive load when a task was spilt across two of these subspaces.

In addition to eccentricities, or visual angles, display devices in non-contiguous configurations exist at different depths. Because the eye has to rapidly refocus when working at multiple depths, some ergonomics recommendations call for displays and documents to exist at a single depth (Ankrum, 1999). However, a study by Jaschinski-Kruza (1990) found that eyestrain was not increased when the user had to refocus their eyes at different depths. It should, however, be noted that a near sighted or far-sighted user has different abilities to see near objects or distant ones comfortably, so exceptions probably apply here (Chapanis & Scarpa, 1967).

Swanson et al. (2001) report a study in which users had to divide their attention between different virtual depths. However, since they were primarily interested in comparing performance between various displays they made no effort to comment on the differences between working at multiple depths as compared to a single depth. In our work, we explicitly explore the effects of working on information at a single depth as compared to multiple depths in physical space.

## 2.3. Notifications

There has recently been a series of studies on the effects of notifications and other kinds of interruptions during everyday computing tasks (for a review, see McFarlane & Latorella, 2002). Most of these studies have shown the disruptive effects of notifications while multitasking (Czerwinski et al., 2000; Gillie & Broadbent, 1989; Kriefeldt & McCarthy, 1981; Maglio & Campbell, 2000). Gillie & Broadbent (1989) manipulated interruption length, similarity to the ongoing task, and the complexity of the interruption. They showed that even rehearsing the position of a target item in the main task does not protect a user from the disruptive effects of an interruption when trying to return to the target afterward. They also discovered that interruptions with similar content could be quite disruptive despite having an extremely short duration, replicating findings from earlier work by Kreifeldt & McCarthy (1981).

Other studies have examined the importance of spatial location of notifications, usually to determine the optimal display location for detection while minimizing disruption. For example, Hess et al. (1999) showed that spatial locations were better than verbal labels, which were in turn better than visual-spatial icons, in supporting the temporary storage and retrieval of information. Their studies also showed that the number of notification updates was inversely related to memory performance for content.

Lim & Wogalter (2000) reported two studies that looked at the placement of static ìbannersî in a web browser window. In their first study, they examined banners in the extreme corners of the display and showed that recognition memory was significantly higher for banners placed in the top left or bottom right corners. Their second study showed that recognition performance was reliably higher for banners centrally located over those in the outer regions of the display. The authors argued that notifications could be made more salient by using this spatial location positioning. Unfortunately, the studies only utilized a single, 21" display, and did not explore larger or multiple display surfaces.

Bartram et al. (2003) specifically explored notifications on larger displays using wider fields of view. The authors probed the perceptual properties of motion in an information-dense display with three experiments. They found that icons with simple motions are more effective than color and shape for notifications that must be delivered with low interruption. Based on these studies, they described several specific advantages and limitations of motion-based icons for larger displays. In addition, the authors varied the field of view affected during their detection tasks, making their guidelines and recommendations generalizable to larger display surfaces than the typical 17" to 21" monitors. However, the authors did not explore the effects of separation that hardware bezels and depth induce, and they focused only on design principles for notification detection. Here we examine multitasking performance while attending to and dismissing notifications across multiple displays.

# 3. Hypotheses

We ran a user study in order to systematically explore the effects of visual separation and physical discontinuities when distributing information across multiple displays while multitasking in a single user desktop scenario. We initially hypothesized that:

- Eccentricity effects suggest that the further two pieces of information are from each other in the visual field, the harder it is to divide attention between them. Thus, we expected that separating information by wider visual angles would be accompanied by a visible decrease in task performance on our tasks.
- Even at equal visual angles, information divided by physical discontinuities such as monitor bezels or depth is harder to treat as a single unit and thus requires more cognitive resources for divided attention tasks. We expected the extra cognitive load to result in decreased task performance.

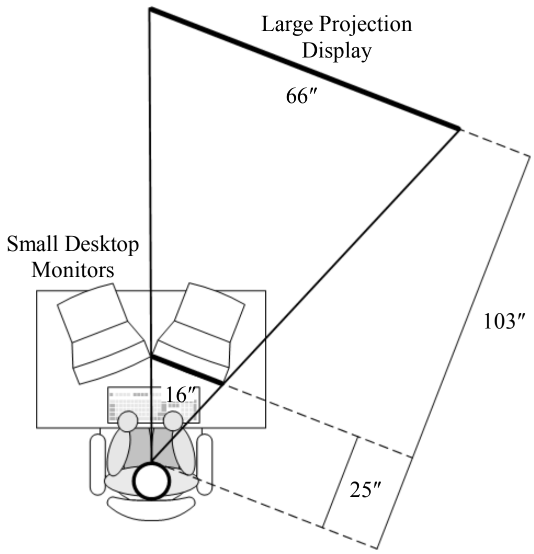



**Figure 1: Experiment setup. Visual angle held constant between the small display and large display conditions.**

# 4. Experiment

## 4.1. Participants

Twenty-four (12 female) users from the Greater Puget Sound area participated in the study. Users were intermediate to advanced Windows users with normal or corrected-to-normal eyesight. They ranged from 18 to 55 years of age (mean: 36.9). Users received software gratuity for their participation.

## 4.2. Experiment and Setup

We used three displays, two NEC MultiSync FE1250 22" monitors and a Sanyo PLC-XP30 LCD projector. All displays ran at a resolution of 1024 x 768 and were calibrated to be of roughly equivalent brightness and contrast. The image on each monitor was 16" wide by 12.5" tall. The image projected on a wall-mounted screen was adjusted to be exactly 66" wide by 49.5" tall. One of the monitors was always the *left display*. We set up the second monitor and projection screen as the *right display*. When either of these displays was viewed from the userís seated position, the visual angle would be identical (Figure 1). We assumed a comfortable viewing distance of 25" for the monitors. In order to get an image with identical visual angles, the large projection display was set up to be 103" away from the user. The center points of both displays were set to be at eye-height, about 60" above the ground. The position of the right monitor was carefully marked so that it could be moved in and out accurately for each condition.

We ran the study on a single 800 MHz Dell computer equipped with a dual-headed nVidia GeForce2 MX graphics card. We duplicated the output for the right display across the monitor and projector using an Inline IN3254 video splitter. Only one of the right displays was turned on at any given time. The user provided input with a standard keyboard and Microsoft IntelliMouse.

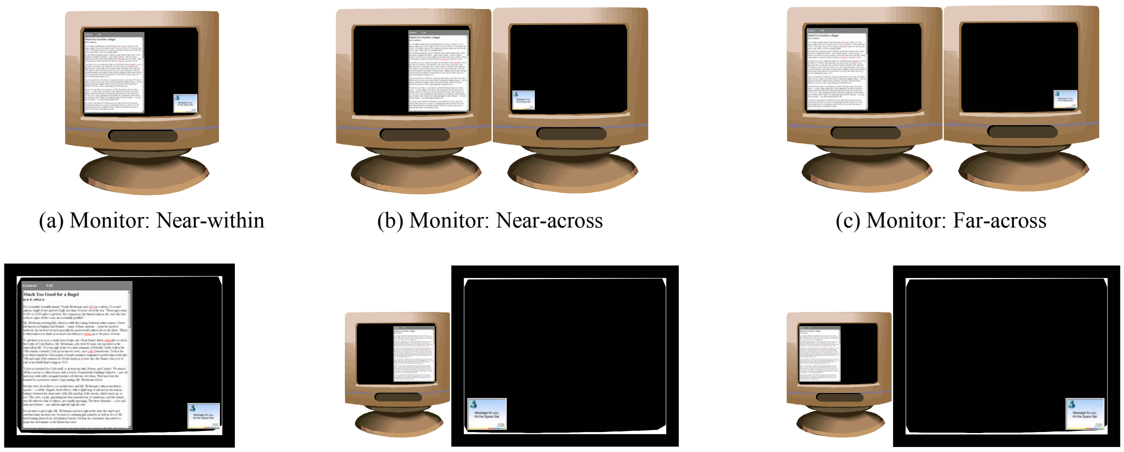
## 4.3. Tasks and Procedure

For this study, we created a compound test comprising a primary task performed in conjunction with a secondary and tertiary task. In the primary task, *proofreading*, users had to identify grammatical errors within a set of text articles. This task was chosen because it is not only visually but also cognitively demanding. We chose seven articles that appeared in the New York Times between January 1998 and December 2000. These articles were selected to be of similar readability and length. Flesch (1948) readability scores for the articles ranged from 46 to 54 (mean: 49.5), representing text at 11-12$^{th}$ grade reading level. Each article was at least 2000 words long.

We introduced errors into each article according to the following rules: (i) each sentence had at most one error, though some had none; (ii) errors were fairly evenly spaced throughout the article; (iii) errors included only subject-verb agreement, inconsistent verb tense, and word order (i.e. two words were flipped). These errors are similar to those introduced by Maglio & Campbell (2000) in their reading tasks. We instructed users to find as many errors as they could in the articles, marking each by double clicking on the word in question. They did not have to suggest corrections to the errors.

The secondary task is one we call *notification detection*. In this task, users had to detect and act upon visual changes outside the focal region of the primary task. This is a common scenario, for example, in system notifications such as instant message arrival or print job completions, which are meant to keep users immediately aware of updated information. These notifications typically call for some form of user response. In our task, users had to detect a pop-up window modeled after the MSN instant messenger notification, and respond by hitting the space bar as quickly as possible.

Properly detecting a notification brought up the tertiary task, *text comparison*. Text comparison is representative of tasks in which the user must cross reference and compare content displayed in multiple locations on the displays. This is an important scenario since one of the benefits of having multiple displays is being able to view, compare and contrast more information simultaneously. In this task, a random set of 4 contiguous lines are selected from the text currently in view in the proofreading task. These lines are highlighted in the actual text as well as replicated in a dialog box which appears on the opposite display. The text in the dialog box is randomly chosen to be either a verbatim representation of the highlighted text or to have a single word order change. Users had to carefully compare the two sets of text and determine whether or not there was a



(a) Monitor: Near-within (b) Monitor: Near-across (c) Monitor: Far-across

(d) Projector: Near-within (e) Projector: Near-across (f) Projector: Far-across

**Figure 2: Display conditions used in the study.**

change in the dialog box. They indicated their answer by clicking on one of two buttons, labeled ësameí or ëdifferentí above the article. After doing this, they resumed proofreading.

In each trial, users were given 4 minutes for the proofreading task. Six notifications were randomly distributed with the constraint that they were at least 20 seconds apart. The clock that showed users how much time remained for proofreading was halted when a notification was detected. It was restarted after the user completed the text comparison task.

## 4.4. Design

We used a within subjects design. Each user performed 1 practice trial and 6 test trails, one in each of the 6 conditions, created using a 2 (display: monitor v. projector) x 3 (distance: near-within v. near-across v. far-across) design (Figure 2).

The visual angle between the primary proofreading task and the secondary and tertiary tasks in the near-within condition was kept exactly the same as in the near-across condition (~27 degrees). The only difference between these two conditions was that the near-within condition was completely contained within one display, whereas the near-across condition was split across two, either having the monitor bezels or the bezels plus a depth discontinuity between the tasks. The far-across condition was designed by keeping the primary task in the same position as in the near-within condition and moving the secondary task as far away on the right display as possible (~55 degrees). The order of conditions and articles used in the primary task were both counterbalanced using Latin Square designs.

Dependent measures included the number of errors correctly identified in the proofreading task, the number of notifications correctly detected, the average reaction time of correctly detected notifications, the number of text comparisons correctly answered, and the average task time for these text comparisons. After the experiment, users filled out a preference survey, indicating the ease of performing the tasks in each of the conditions. The experiment took about 1 hour.

## 4.5. Results and Discussion

### 4.5.1. Overall MANOVA

We submitted the data to a 2 (display: monitor v. projector) x 3 (distance: near-within v. near-across v. far-across) repeated measures multivariate analysis of variance. Each dependent measure is covered separately in the results.

We observed no significant effects or interactions for either the average reaction time to detect a notification or the average reaction time for the text comparison task, at the p=.05 level (all effects were tested at this alpha level). Most users detected all the notifications and there were no significant effects with this measure.

For the number of correct text comparisons, we observed a significant interaction between display and distance, F(2,46)=3.05, p=.05. Post-hoc analyses showed that the near-within and the far-across conditions were borderline significantly different, p=.06. The interaction reached significance because this difference between the near-within and far-across conditions was reliable for the projector (means: 5.167 and 4.625 respectively), though not the monitor condition (means: 5.042 and 4.875), as can be seen in Figure 3. Although the result reaches statistical significance, the effect is fairly small.

For the number of correct errors found in the proofreading task, the interaction between size and distance reached borderline significance, F(2,46)=2.6, p=.085. Again this result was driven by a larger difference between the near-within and far-across conditions on the projection display (means: 7.875 and 7.000 respectively) but not the monitor (means: 7.667

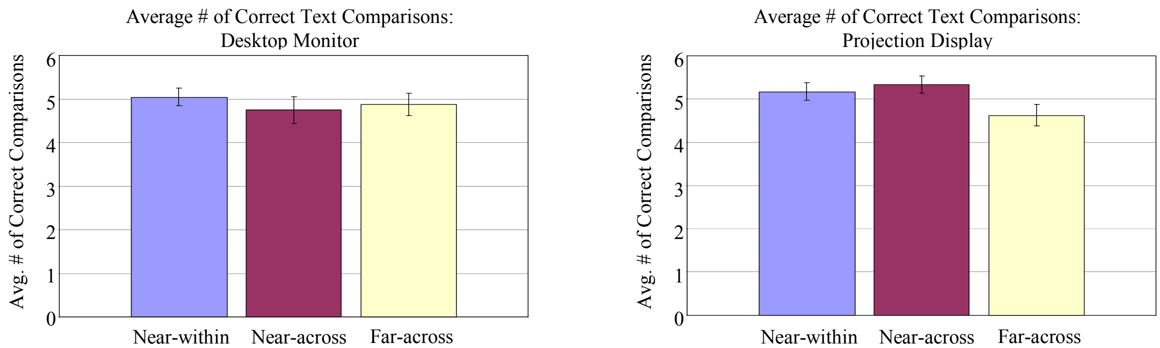



**Figure 3: Though we saw no significant differences for the monitors (*left*), for average number of correct text comparisons, there was a significant difference between near-within and far-across conditions for the projector conditions (*right*).**

and 8.000), as seen in Figure 4. These effects are also relatively small.

These performance results ran counter to our initial hypotheses. We expected large, detrimental effects from separation of information in the visual field. We also expected detrimental effects from the physical discontinuity caused by the bezel and the separation in depth. For the time to detect notifications and for the text comparison times, we observed no effects of separation, bezel, or depth. In fact, we did not observe a significant main effect of visual separation in the performance data for any dependent measure. Instead, we observed a small but reliable interaction between display and the distance variable for the overall proofreading correct and text comparison correct measures. This interaction could be best described as resulting from the differences between the near-within and far-across conditions being stronger for the projector condition.

### 4.5.2. Satisfaction Data

After the study, participants were asked which display configuration they preferred for performing the tasks involved. Surprisingly, 14 out of 24 participants stated that they preferred the smaller, 22" CRT for their primary task, significant by binomial test, p=.006. Nine participants preferred the larger, wall display for the primary task, and this was not significant. One participant stated ìno preferenceî as their response to this question.

Participants were evenly split in terms of which configuration they preferred (same screen, split screen, or neither) for working on all experimental tasks. 10 preferred the tasks on the same screen, 11 preferred them on split screens, and 2 participants stated no preference.

This result is quite interesting, and converges nicely with some of the performance-based results we observed during the experiment. It appears that users are evenly split in how they would like their information presented around the bezel, and the deleterious effects appear to be much less important than we had hypothesized. The fact that about half our participants preferred to split their task across the bezels (even when distance to a larger, wall display is involved) is a fascinating one. We assert that the bezel might be playing some role that allows users to spatially address their information workspace in a way they perceive to be beneficial to the task, as asserted by Grudin (2000). However, this resulted

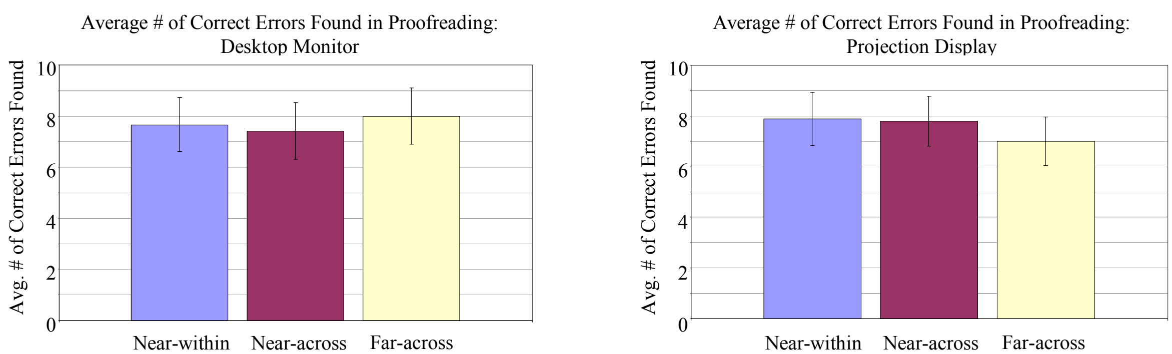



**Figure 4: Though we saw no significant differences for the monitors (*left*) for average number of errors correctly found, there was a significant difference between near-within and far-across for the projector conditions (*right*).**

neither in a reliable benefit nor detriment to task performance. Exploring this hypothesis more deeply remains as future work.

## 5. Design Recommendations

For the tasks chosen in this study, we saw significant performance differences between the near-within and far-across conditions, but only when information was split between the desktop monitor and the projection display. This indicates that, even at similar visual angles, placing information further in the periphery on displays that are separated in depth is more detrimental to performance than the corresponding position at similar depths. However, it should be noted that for our tasks, effects seen were relatively small (about a 10% performance decrement), and designers, aware of the small differences present, can weigh the importance of the information to be displayed with this trade-off in mind.

Interestingly, we saw no effects of physical discontinuities, introduced either by monitor bezels or by the depth difference between the monitor and projection display. This was surprising, but implies that designers might have more freedom when splitting information across boundaries than we had anticipated. We do not doubt that there are tasks which will be hurt by splitting information across physical discontinuities, but our set of tasks (proofreading and monitoring) do not seem to fall heavily into that category.

## 6. Conclusion and Future Work

In this paper, we have reported a study examining the effects of visual separation and physical discontinuities when distributing information across multiple displays. Study tasks were chosen to be representative of tasks carried out by information workers while multitasking so as to increase the generalizability of the results to future display systems and user interface designs for single user desktop scenarios. The study demonstrated that there is a reliable, though relatively small, detrimental effect on performance from separating information within the visual field when it is further separated by depth. Also, counter to our hypotheses, physical discontinuities introduced by bezels as well as by differences in depth alone do not seem to have an effect on performance on the set of tasks we have chosen. We have presented design recommendations that follow from these results.

We would like to extend this work in several directions. We would like to add further ecological validity by introducing unrelated notification content that serves as extra distraction. In the current study, we displayed only information that was relevant to the tasks the user was performing. Previous research has shown that this should make visual search and detection tasks harder (Czerwinski et al., 2000; Gillie & Broadbent, 1989), but we do not know the effects of our manipulations in this situation.

Also, more work needs to be done to explore scenarios that involve collaboration and interruption, as well as different tasks within the same experimental framework. For example, we could use a monitoring task, in which users have to simultaneously watch and act upon multiple objects while communicating and sharing information with other colleagues. Alternatively, we could extend this work to tasks in which depth cues or continuity of the information is important, such as in certain 3D environments. Results from this work have critical implications both on the design of workplaces as well as on software and applications operating in these new display configurations.

## 7. Acknowledgements

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