Put Them Where? Towards Guidelines for Positioning Large Displays in Interactive Workspaces

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Abstract. Multiple large displays are being increasingly used in interactive workspaces to enhance individual and group work. However, little research has been conducted to determine whether various configurations of large displays impact users or their tasks differently. We show that such an impact exists, and take steps towards developing guidelines for how to effectively arrange large displays in interactive workspaces. For two large displays, we manipulated their physical separation, angle between them, and symmetry when facing each other and measured time on task, subjective workload, and satisfaction for application relocation tasks. From the results, we produced three useful guidelines: (i) displays can be separated on a horizontal plane up to a subtended visual angle of 45°, (ii) a display should not be placed behind a user, but if necessary, it should be offset relative to the user, and (iii) displays should be positioned at a 45° angle relative to each other rather than being orthogonal. As the use of large displays is increasing, these guidelines should have a broad, practical impact.

1 Introduction

Multiple large displays are being increasingly used in workspaces such as meeting rooms, design studios, and research labs to improve individual and group work. For example, large displays enable juxtaposition of alternative ideas [3], support awareness of peripheral information [27], and enable more effective discussion of digital information [25]. Workspaces that are equipped with multiple large displays and other, interconnected computing devices are known as *interactive workspaces* [15].

Upon acquiring large displays, however, one faces the practical and significant question of whether or not their position in the workspace has an impact on their use. For example, does a gap between displays adversely affect users? If so, how much of a gap is allowable? If the physical limits of a room do not allow displays to be placed adjacent to each other, does changing the angle or symmetry between the displays affect their use? If so, how much of an angle is appropriate or how much would placing displays behind users affect them? In addition, as large displays are often affixed to a wall, the impacts associated with display placement can be permanent.

While researchers have investigated how people use multiple desktop monitors in work practice [8] and have developed guidelines on how to configure multiple small

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displays [2, 12, 13], our research seeks to provide guidelines – supported by empirical evidence – for how to effectively configure large displays in interactive workspaces.

In our experiment, we empirically compared several configurations of large displays; we varied the distance between displays along a horizontal plane, oriented displays at different angles, and positioned displays with varying amounts of symmetry. To test these configurations, we selected the task of moving an application window between displays – a common and frequent task when arranging information or managing applications among multiple displays in interactive workspaces [3, 20].

We compared the configurations based on task performance, subjective workload, and user satisfaction for performing application relocation tasks. For these tasks, our results produced three practical guidelines for configuring large displays: (i) displays can be separated on a horizontal plane up to a maximum visual angle of 45° (Figure 1a-b), (ii) a display should not be placed behind a user, but if necessary, it should be offset relative to the user (Figure 1h-i), (iii) displays should be positioned at a 45° or possibly lower angle relative to one another (Figure 1d). These guidelines are important because they show that following common practices such as positioning displays symmetrical or orthogonal to each other may result in less effective configurations.

2 Related Work

In this section, we describe how our work fits with interactive workspaces, the use of multiple small and large displays, and the ergonomics of computer monitors.

2.1 Interactive Workspaces

An interactive workspace is a physical space where users interact with small/private and large/shared displays to perform individual or group work. Several distributed infrastructures have been developed that enable multiple, heterogeneous devices to function as a single, connected workspace – these include Gaia [21], iRos [14], and Aura [24]. On top of these infrastructures, many interfaces have been developed to enable seamless redirection of input and relocation of applications [3, 4, 7, 16, 17, 19, 20]. However, our work is the first to investigate how different configurations of large displays affect performance, workload, and satisfaction on relocation tasks.

While the design space encompasses many different types of tasks, interfaces, and movements between displays, we focused on a realistic but specific scenario. This allowed for a large and necessary degree of experimental control. Our scenario is the intersection of the three activities commonly performed in interactive spaces: relocating an application [3, 17], using a virtual paths interface [4, 16], and interacting between large displays [5, 22, 26].

2.2 Use of Multiple Small and Large Displays

In a study of multiple monitor usage in the workplace [8], Grudin found that most users divide information between the monitors – the focal monitor is used for main tasks while the peripheral monitor is used for secondary tasks. Because information is now divided between multiple monitors, users employ different window management techniques as seen in Hutchings et al [10, 11]. In these configurations, a common and frequent task is the moving of applications between the displays. Our choice of the experimental task was selected to reflect this scenario of use and show how performing this task may be affected by different configurations of large displays.

In [27], a user study was performed to test how separating information by various visual angles and monitor bezels affects performance for comparing text and detecting changes to information. In contrast, our study measures the impacts of wider visual angles and other configurations of large displays, and uses a task that requires actively moving an application across displays rather than passive monitoring.

Research has shown that using large displays can improve task performance due to more available screen space [5, 22, 26]. By comparing different configurations of large displays for application relocation performance, our study seeks to recommend how to configure large displays such that these performance gains are maximized.

2.3 Ergonomics of Desktop Monitors

Ergonomics research has developed guidelines for positioning desktop monitors in the workplace [2, 12, 13]. Sommerich found that the viewing angle of a monitor affects posture, performance, and preference [23]. Ankrum investigated the optimal range of viewing distance of desktop monitors and recommends a minimum distance of 25” [1]. This area of work supports our hypothesis that the manipulation of angle and distance of large displays will have an impact on users and also demonstrates how the application of a few specific guidelines could have a large practical impact. Our research focuses on developing guidelines for positioning multiple large displays in an interactive workspace to improve performance and satisfaction on a common task.

3 User study

The purpose of our user study was to evaluate how different configurations of large displays affect users when moving applications among them. Specifically, the study was designed to answer the following questions:

- How does the physical separation between large displays affect performance, subjective workload, and satisfaction when moving applications?
- How does the angle between large displays affect performance, subjective workload, and satisfaction when moving applications?
- How does the symmetry between a large display in front of a user and another behind the user affect these same measures when moving applications?

From the results, we want to begin developing guidelines on how to configure large displays for effective use in interactive workspaces.

3.1 Experimental Design

The study used a partial-factorial, within-subjects design. There were four factors– Distance (63”, 109”, 300”), Angle (45°, 60°, 90°), Symmetry (no-offset, half-offset, one-offset), and Trial (each of the sixteen application movements). The Distance, Angle, and Symmetry factors were tested as three separate experiments in which three physical configurations of the displays were compared. The ordering of the factors and the configurations within each factor followed a Latin Square design. Because configurations were a function of the factor, they were not crossed in the design.

Twenty users (10 female) participated in the study. Users consisted of undergraduate and graduate students from various non-engineering departments at our institution, and members of the surrounding community. Ages ranged from 18 to over 40.

3.2 Interactive Workspace

The interactive workspace used in this study was comprised of a meeting table and two 61" plasma displays with resolution 1360×768. A workstation running Windows XP equipped with a multi-head graphics card was used to drive the displays. Camtasia was used to record a user's screen interaction on both displays.

To achieve the necessary level of experimental control, we limited the number of large displays used in the experiment to two. The displays were mounted on moveable stands to enable them to be quickly re-positioned in the workspace. A key property of our experimental design is that while the *physical* position of the displays was changed, the *virtual* distance between the displays always remained the same.

3.3 Geometric Properties and Configurations of the Large Displays

We varied the physical configurations of two large displays by varying the distance between the displays along the same horizontal plane (Distance), the amount of angle between the displays (Angle), and the amount of overlap between the displays (Symmetry). The configurations are shown in Figure 1. We selected these geometric properties because they represent how large displays are often configured in practice - displays positioned along a horizontal plane, displays positioned orthogonal to each other, and displays positioned so that they are aligned when facing each other. While these configurations are often selected based on aesthetics or physical dimensions of a workspace, our goal is to provide guidelines backed by empirical evidence that can be used to help determine how to arrange large displays for effective use.

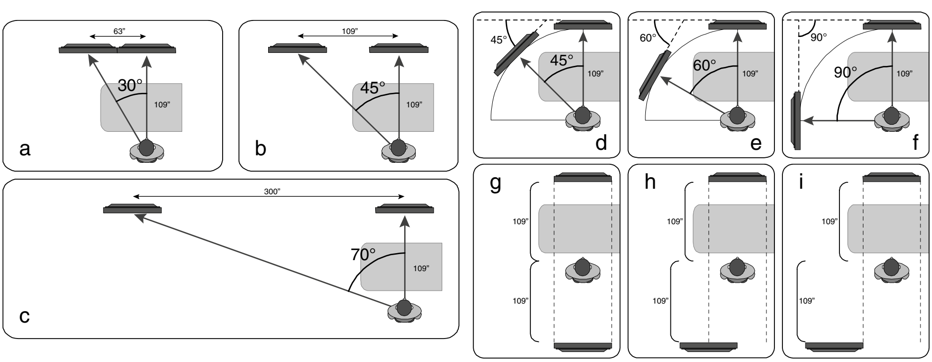


Fig. 1. The physical configurations of Distance (a-c), Angle (d-f), and Symmetry (g-i). One display always remained directly in a user's field of view at a distance of 109", while the location of the other display was manipulated.

In the study, one display always remained directly in front of a user seated at the table, as users would ostensibly want at least one display to be directly in their field of view. The distance to the fixed display was 109", which allowed content on the display to be easily viewed when seated at the table. The position of the other display was manipulated according to the configurations discussed next. Positions of the second display were marked on the floor to ensure consistency across users.

Distance. We compared distances of 63" (Fig. 1a), 109" (Fig. 1b), and 300" (Fig. 1c) between the centers of the displays. Distances were calculated based on two parts of a user's visual field [6, 18]—the useful field of view (extends to 30°) and peripheral field of view (extends to 100°). We positioned the second display so that it would be within the useful visual field (30°), slightly outside the useful visual field (45°), and close to the periphery (70°). We could not place the display at the edge of a user's periphery (100°) due to the physical limitations of our workspace. The display was positioned such that lines drawn from the user to the centers of the displays subtended the desired visual angle. We then measured the distance between the centers of the displays: 30° mapped to 63", 45° mapped to 109", and 70° mapped to 300".

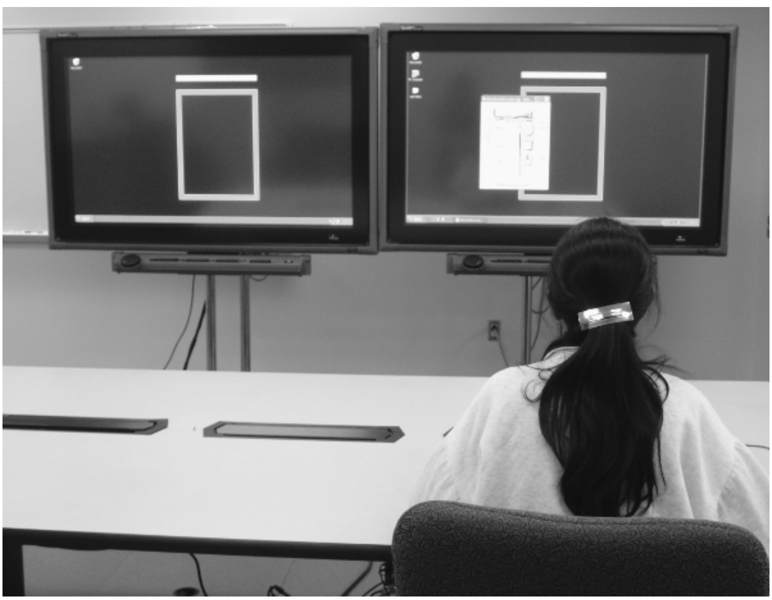


Fig. 2. A user is performing the experimental task for the 63" distance configuration. The user is moving an Internet Explorer application from the display on the right to the display on the left. After moving the application into the target box on the left, the user selects the rectangular bar above it. Each movement was a single trial and sixteen trials (resulting in a back and forth movement of the application) were performed in each configuration. The target boxes were used to ensure that the application was moved the same virtual distance.

Angle. We compared angles of 45° (Fig. 1d), 60° (Fig. 1e), and 90° (Fig. 1f). Because large displays are often wall-mounted, they are typically constrained to be on the same (0°, or orthogonal planes (90°). We wanted to investigate how other angles would affect a user within this range. Since a 0° configuration was similar to Distance, we started with the minimum angle that our pilot users felt was noticeably different from 0°, which occurred at 45°. The maximum angle selected was 90°, as this represents many existing configurations, and 60° was used as a median case. To create the angles, we moved the second display along a circular path from the fixed display until it reached the desired angle.

Symmetry. We compared three configurations of symmetry—the two displays aligned (no-offset, Fig. 1g), one display half overlapping the other (half-offset, Fig. 1h), and one display fully offset from the other (one-offset, Fig. 1i). The second display was positioned and moved along a horizontal plane behind the user. While these configurations may not be ideal, they are *realistic* since the physical limits of a workspace may cause one or more displays to be placed behind a user. We have informally observed displays configured this way in many research labs.

3.4 Experimental Task

The experimental task was to move an Internet Explorer application, with the resize and maximize buttons disabled, from the target box of one display to the target box of the other display. Figure 2 shows a user performing the task. This task was selected because relocating applications to spread information or to manage screen space across displays is a common and frequent task in an interactive workspace [3]. To ensure that a user performed a focused movement as opposed to a ballistic movement, which is a rapid, involuntary movement (e.g. a quick flick of the wrist) [28], a user selected a rectangular bar just above the target box after moving the application.

A target box was 20% larger than the application window and was located in the center of a screen. The target boxes provided a consistent starting and stopping point for each movement of the application and ensured that the application was always moved about the same virtual distance. A user performed this task sixteen times in each configuration to compensate for learning effects on the early trials.

3.5 Procedure

Upon arriving at the lab, we went through an informed consent process with the user. The user filled out a demographic questionnaire, was given a demonstration of the task, and practiced the task. Then, the user was instructed to perform the experimental task as quickly and accurately as possible for a specific configuration of the displays. A user performed the task sixteen times in each configuration. Once complete, the user filled out a NASA-TLX and satisfaction questionnaire. This process was repeated two more times for the other two configurations of the geometric property (e.g. Distance). A user then ranked the difficulty of performing the task in the three configurations. This entire process was then repeated two more times for the remaining geometries. The orders of the geometries and the configurations within each geometry followed a Latin Square design. The study lasted no more than an hour for a user.

3.6 Measurements

In this study, we measured:

- *Time on task (TOT)*. The time on task was measured from when the title bar of the application was selected to when the application was located in the target box and the mouse started moving towards the horizontal bar. Measurements were made from analysis of the timestamps in the screen interaction videos.
- *Subjective workload*. The NASA-TLX was used to measure subjective workload along the standard dimensions of *mental demand*, *physical demand*, *own performance*, *effort*, and *frustration* [9]. While the user was asked to complete the task as quickly and as accurately as possible, no external time limit was imposed, thus we did not include *temporal demand* on the TLX. A continuous scale from Low to High was used for each dimension to allow fine-grained responses from the user.
- *User satisfaction*. A user rated their annoyance, confusion, and overall satisfaction for performing the tasks in each configuration. A user also rated how natural the connection was between the displays. Ratings were made using the same response structure as the TLX. Also, a user ranked the difficulty of performing the tasks in each configuration (e.g., Distance) and explained why they gave the rankings.

4 Results

In this section we discuss how the configurations of Distance, Symmetry, and Angle affected time on task, subjective workload, and user satisfaction. Trial did not affect any of the measures, so it will not be discussed further. To account for any learning effects, the first six trials of a user's performance data in each configuration were removed, leaving ten experimental trials in each configuration for the analysis.

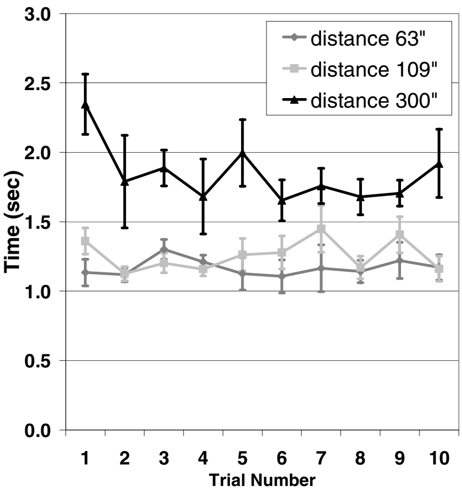
The results for time on task, subjective workload, and user satisfaction for Distance and Symmetry are shown in Figures 3 and 4, respectively.

4.1 Distance

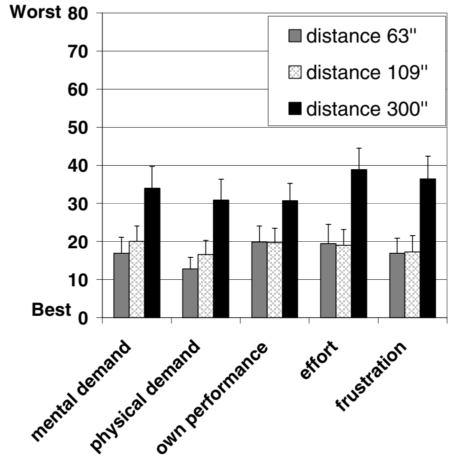
Time on Task. An ANOVA showed that Distance had a main effect on TOT ($F(2,36)=43.63$, $p<0.001$). Post-hoc analysis showed that users moved the application faster at distance 63" ($\mu=1.17$s) and distance 109" ($\mu=1.26$s) than at distance 300" ($\mu=1.84$s, $p<0.001$, $p<0.041$, respectively). There was no significant difference between 63" and 109".

Although the virtual distance between the target boxes was held constant, users performed the task about 57% slower when the displays were furthest apart than when they were closest together. The decrease may be attributed to users perceiving having to move the application across the gap between the displays or to increased difficulty positioning the application within the target box when the display was further away.

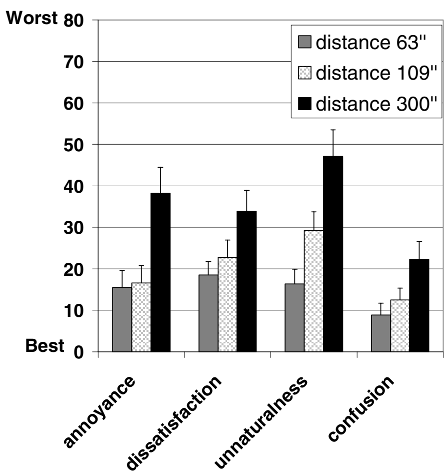
For distance 109", however, users completed the task as quickly as for distance 63" despite the physical separation. This shows that separation of displays does not affect relocation performance as long as the visual angle formed for a user is less than 45°.



(a) Time on Task



(b) Subjective workload



(c) User satisfaction

Difficulty	63’’	109’’	300’’
Easiest	17	3	0
Intermediate	3	15	2
Most difficult	0	2	18

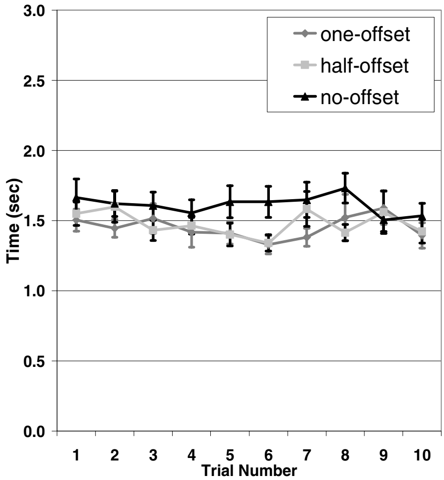
(d) Rank counts of difficulty

Fig. 3. Time on task, subjective workload, and user satisfaction results for Distance

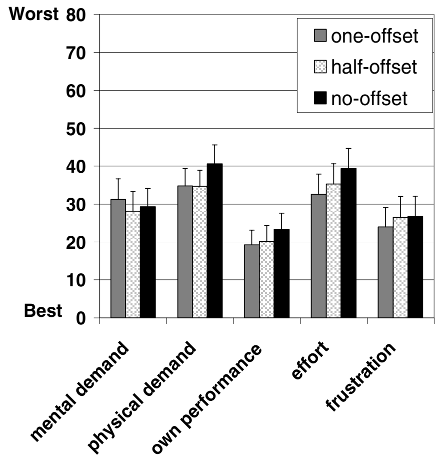
Subjective Workload. A MANOVA showed that Distance had a main effect on subjective workload (Wilks’ Λ=0.44, $\underline{F}$=(10,68)=3.43, $\underline{p}$<0.001). Univariate analysis showed that there was a main effect on mental demand ($\underline{F}$(1.33, 25.26)=15.61, $\underline{p}$<0.001), physical demand ($\underline{F}$(1.28, 24.22)=12.24, $\underline{p}$<0.001), own performance ($\underline{F}$(2,38)=4.59, $\underline{p}$<0.016), effort ($\underline{F}$(2,38)=11.57, $\underline{p}$<0.001), and frustration

($\underline{F}(2,38)=12.54$, $\underline{p}<0.001$). Post-hoc analysis showed that for distance 300", users reported more mental demand ($\mu=34.0$), physical demand ($\mu=30.9$), performance demand ($\mu=30.7$), effort ($\mu=39.0$), frustration ($\mu=36.5$) than both distance 63" ($\mu=16.95$, $\mu=12.75$, $\mu=19.9$, $\mu=19.4$, $\mu=17.0$, respectively, with $\underline{p}<0.014$ in each case) and distance 109" ($\mu=20.05$, $\mu=16.6$, $\mu=19.7$, $\mu=19.0$, $\mu=17.25$, respectively, with $\underline{p}\leq 0.020$ in each case). There was no difference between distances 63" and 109".

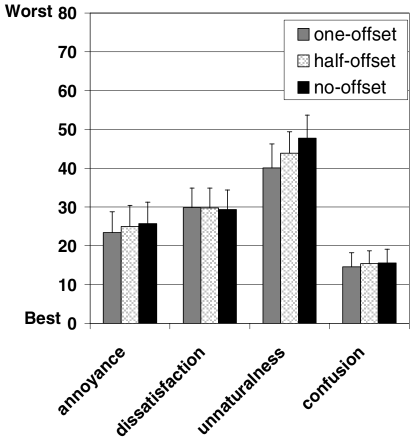
Results show that physical separation of displays does not cause an increase in subjective workload as long as the user's visual angle of the displays was less than 45°.



(a) Time on Task



(b) Subjective workload



(c) User satisfaction

Difficulty	One-offset	Half-offset	No-offset
Easiest	12	6	2
Intermediate	4	13	3
Most difficult	4	1	15

(d) Rank counts of difficulty

Fig. 4. Time on task, subjective workload, and user satisfaction results for Symmetry

User Satisfaction. A MANOVA showed that Distance had a main effect on user satisfaction (Wilks' $\Lambda=0.38$, $F(8,70)=5.52$, $p<0.001$). Univariate analysis showed that Distance had a main effect on annoyance ($F(1.54, 29.17)=15.10$, $p<0.001$), satisfaction ($F(2,38)=10.80$, $p<0.001$), naturalness ($F(2,38)=23.71$, $p<0.001$), and confusion ($F(2,38)=7.23$, $p<0.002$). Post-hoc analysis showed that distance 300" caused more annoyance ($\mu=38.3$), dissatisfaction ($\mu=33.9$), unnaturalness ($\mu=47.0$), and confusion ($\mu=22.3$) than distance 63" ($\mu=15.5$, $\mu=18.5$, $\mu=16.4$, $\mu=8.9$, respectively, $p<0.002$ in each case). Distance 300" caused more annoyance, dissatisfaction, and unnaturalness than distance 109" ($\mu=16.6$, $\mu=22.8$, $\mu=29.3$, respectively, $p<0.016$ in each case). Distance 109" was rated more unnatural than distance 63" ($\mu=16.4$, $p<0.009$).

A two-way contingency table analysis showed that Distance had a main effect on users' ranking of task difficulty (Pearson $\chi^2(4,N=60)=69.60$, $p<0.001$). Users ranked distance 63" as the easiest and distance 300" as the most difficult configuration.

Consistent with previous results, physical separation did not cause a substantive decrease in user satisfaction until the displays move beyond 45° in the user's visual field.

4.2 Symmetry

Time on Task. Symmetry had a main effect on TOT ($F(2,38)=6.21$, $p<0.005$). Post-hoc analysis showed that users moved the application faster with one-offset symmetry ($\mu=1.45$s) and half-offset symmetry ($\mu=1.47$s) than no-offset ($\mu=1.61$s, $p<0.014$, $p<0.022$, respectively). There was no significant difference between half-offset and one-offset symmetry. Results show that performance decreased about 11% as the second display was moved directly behind a user. The performance decrease may be due to the increased amount of head turn required to complete the task.

Subjective Workload. Symmetry had a main effect on subjective workload (Wilks' $\Lambda=0.59$, $F(10,68)=2.09$, $p<0.037$). Univariate analysis showed that there was a main effect only for physical demand ($F(2,38)=4.45$, $p<0.018$). Post-hoc analysis showed that no-offset symmetry caused more physical demand ($\mu=40.6$) than one-offset symmetry ($\mu=34.8$, $p<0.059$). No other differences were found. Results generally show that as the second display is moved further behind a user, more subjective workload is experienced. This is consistent with the results for task performance.

User Satisfaction. Symmetry did not affect user satisfaction (Wilks' $\Lambda=0.82$, $F(8, 70)=0.90$, $p<0.52$), although satisfaction tended to decrease as the second display was moved further behind the user. A two-way contingency table analysis showed that Symmetry did affect ranking of task difficulty (Pearson $\chi^2(4,N=60)=33.00$, $p<0.001$). Users ranked one-offset as the easiest and the no-offset as the most difficult configuration for performing the task. While changes in Symmetry did not impact ratings of satisfaction, users highly preferred the one-offset configuration for performing the task.

4.3 Angle

Angle had no main effect on TOT ($F(2,9)=0.80$, $p<0.46$). Users required about the same time to perform the task across configurations. Angle did not affect subjective workload (Wilks' Λ=0.79, $\underline{F}(10,68)=0.84$, $\underline{p}<0.59$), though ratings of workload tended to increase as the angle between the displays increased.

While satisfaction tended to decrease as the angle between the displays increased, Angle did not affect user satisfaction (Wilks' Λ=0.73, $\underline{F}(8,66)=1.39$, $\underline{p}<0.22$). However, a two-way contingency table analysis showed that Angle did affect ranking of task difficulty (Pearson $\chi^2(4,N=60)=32.10$, $\underline{p}<0.001$). Users ranked 45° (count=13) as the easiest configuration and 90° (count=14) as the most difficult configuration for performing the task.

While changes in Angle did not impact ratings of satisfaction, users highly preferred the smallest angle between the displays for performing the task.

5 Lessons Learned

From the results of our study, we learned that:

- *Different configurations of large displays have different impacts on users and their tasks*. Results show that various configurations of large displays affect time on task, subjective workload, and user satisfaction differently when performing application relocations tasks. This validates a need for guidelines for how to physically arrange large displays for effective use in interactive workspaces.
- *Displays can be physically separated on a horizontal plane as long as the visual angle subtended is less than 45°*. Results show that increasing the physical separation between the displays from the edges touching (a user's visual angle of 30°) to a small gap (45°) did not cause a negative change in performance, subjective workload, or satisfaction. Beyond a user's visual angle of 45°, however, each of these measures meaningfully changed in the negative direction. This suggests the allowable distance between the outermost displays should subtend a visual angle of no more than 45° for a user. Our results contradict the accepted intuition that displays must be positioned with their edges adjoined in order to be used effectively.
- *A display should not be placed behind a user, but if necessary, it should be offset relative to the user*. In the one-offset configuration (Figure 1i), users performed tasks faster, experienced less workload, and gave higher rankings than in the other configurations. Despite this preference, users overall disliked having a display positioned behind them (Figure 1g-i). Several users commented that they did not like having to turn their head or rotate their body to perform the task—"Why would you want to do this [placing display behind the user]?", "This is terrible". These comments are consistent with other research [3], which indicates that head turns and body movement can provide additional metrics by which to evaluate user interfaces in interactive workspaces.
- *Displays should be positioned at a 45° or possibly lower angle relative to each other*. The orthogonal (Figure 1f) configuration tended to be worse on all measures and was overwhelmingly ranked as the worst configuration. One user commented, "the relationship between the two displays [at 90°] was awkward; I had to turn my head more." However, the 45° configuration was ranked the best because users felt they could view the displays more easily. One user stated "the 45 angle didn't involve much turning, it was easy to glance from one to the other". Thus, if displays

cannot be positioned along the same horizontal plane, they should be placed with the smallest angle between them rather than orthogonal to each other, which may require the use of moveable stands.

These guidelines are most applicable when users want to rapidly spread information among displays in an interactive workspace, and may not be applicable when users want to visualize large, contiguous data sets such as an architectural design across multiple displays. However, because the former is a common use of interactive workspaces, our guidelines will have a broad and practical impact.

6 Conclusion and Future Work

Large displays are being increasingly used in interactive workspaces to enhance individual and group work. However, there are few, if any guidelines to draw upon when considering how to physically arrange large displays. Through an experiment comparing different configurations of large displays, our work has made two significant contributions. First, our results show that different configurations of large displays have meaningfully different impacts on users and their tasks, validating the need for guidelines about effective arrangement. Second, our results have produced an initial set of practical guidelines on how to arrange large displays for effective use in interactive workspaces. These guidelines are important because they show that following some common practices such as positioning displays symmetrical or orthogonal to each other may result in less effective configurations.

In the future, we want to compare configurations of large displays for additional tasks such as redirecting input, juxtaposing ideas, and monitoring information. Also, we want to evaluate how various configurations of the displays impact interaction techniques for performing those tasks. Results from future work will continue to provide guidelines that will facilitate more productive use of interactive workspaces.

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