The Effects of Curving Large, High-Resolution Displays on User Performance

Lauren Marcy Shupp

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Dr. Chris North
Dr. Doug Bowman
Dr. Bill Carstensen

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ABSTRACT

Tiling multiple monitors to increase the amount of screen space has become an area of great interest to researchers. While previous research has shown user performance benefits when tiling multiple monitors, little research has analyzed whether much larger high-resolution displays result in better user performance. The work in this paper evaluates user performance on an even larger, twenty-four monitor, high-resolution (96 DPI), high pixel-count (approximately 32 million pixels) display for single-users in both flat and curved forms. The first experiment compares user performance time, accuracy, and mental workload on multi-scale geospatial search, route tracing, and comparison tasks across one, twelve (4×3), and twenty-four (8×3) tiled monitor configurations. Using the same tasks, we evaluated conditions that uniformly curve the twelve and twenty-four monitor displays. Results show that, depending on the task, larger viewport sizes improve performance time with less user frustration. Findings also reveal that curving large displays improves performance time as users interacted with less strenuous physical navigation on the curved conditions.

A second study sought to understand why curving the display, effectively bringing all pixels into visible range, improved performance so as to provide guidelines for using such large displays. The study tested for region biases, performance gaps in comparing virtually distant objects, and degree of detail of user insights while measuring the physical navigation required. Results clearly show that significantly less movement is required when physically navigating the curved display. Performance measures reveal that users favor the left regions of the flat display, while there appears to be no region bias on the curved display. Furthermore, user performance time increased as the virtual distance between objects increased, and there is a tradeoff in insight detail between the two forms. In conclusion, larger, high-resolution displays improve user performance, and curving such displays further improves performance, removing any biases towards regions of the display, potentially reducing the performance drop of virtually far apart objects, reducing the amount of physical navigation necessary, and enabling more detailed insights. Based on these findings, geospatial analysts should be able to curve multiple monitor displays – if space is an issue, start curving once the display reaches four or five monitors wide – and seek quickly reconfigurable displays to balance the user perspective for insights.

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

Tiling multiple monitors to increase the amount of screen space has become an area of great interest to researchers. Of the display technologies currently available (e.g. rear-projection blocks), tiling LCD panel monitors, as evaluated in this work, is by far the most affordable method of building a relatively high-resolution display. Until recently, resolution (pixel density) was compromised in order to increase the size of a display (i.e. overhead projector). By tiling monitors, the size of a display can increase while maintaining a high-resolution. This is increasing the pixel-count while holding resolution constant, resulting in a large display that is now high-resolution.

Previous research shows user performance benefits when using multiple monitors [9, 10, 15]. Researchers in information visualization are interested in looking beyond the limitations of the single monitor paradigm to see what users can gain from increasing the screen space available to visualizing data. With larger displays, users can have an extensive overview of the data. With high-resolution displays, users can use natural physical navigation to access finer details of the data. Although research has found benefits for high-resolution displays as large as 3×3 monitors, there is great potential for using much larger high-resolution displays as power desktops for single-users [6, 9, 10]. The work in this paper discusses two evaluations of single-user performance on an even larger, twenty-four monitor, high-resolution (96 DPI), high pixel-count (approximately 32 million pixel) display in both flat and curved forms.

The goal of the first experiment was to determine whether single-users can benefit from using a display as large as ours (viewport size) for two-dimensional, multi-scale geospatial tasks, and whether the form of the display is a significant factor in user performance (curvature). If there are performance benefits at twenty-four monitors, perhaps there will continue to be performance benefits on even larger displays. Furthermore, if there are performance benefits when curving a large, high-resolution display, by bringing all the pixels into visible range and changing the physical navigation necessary to complete tasks, then perhaps the form of displays of equal or greater magnitude is an increasingly important factor. Because there is great need for guidelines for future display technologies, my second experiment further evaluates the benefits of curving the display.

Figure 1.1: Twenty-four monitor display in the curved form with Vicon motion trackers

The second experiment evaluated why users perform faster on curved displays using static two-dimensional geospatial tasks. The study determined why bringing all pixels into visible range improves performance. Does curving the display improve performance because the position of the details no longer matters? Does curving the display allow users to compare virtually distant objects better? Answers to both questions will aid in the design of interfaces for these displays as well as better inform users concerned with precious office space on what form is sufficient or necessary for their needs. Furthermore, since users in the curved form have all the pixels, essentially all the details, available to them at once, is there a tradeoff of an insight's degree of detail on the two forms? In the area of information visualization, enabling the user to make observations about large data sets is important. Most tasks in previous evaluations have clear right or wrong answers to make this determination, making it relatively easy to measure user performance. However, as illustrated by Saraiya et al. it is equally important to understand the types of observations and insights users can gain from visualizations [29]. Therefore, insight-based evaluations should also be considered when evaluating the form factor of large, high-resolution displays.

A likely user of displays for tasks similar to those in this research is an intelligence image analyst, who would realistically be examining imagery every day for most of the work day. Therefore, the performance benefits of single tasks found in this paper aggregate over time, resulting in a greater overall benefit. This is an analytic force multiplier, allowing the same workforce to perform as if a greater number of people.

Chapter 2

Research Questions

The research questions in the first experiment were:

1. What happens to user performance with increasingly larger (greater pixel-count) displays on geospatial tasks (Figure 5.1)?
2. Does the curvature of such large displays affect user performance for geospatial tasks (Figure 5.2)?

The corresponding hypotheses were:

1. User performance improves with larger displays because users have more data and more context visible at once, and will efficiently navigate the information physically using eye, head, and body movement.
2. User performance improves on a curved display, because curving the display decreases the amount of time spent physically navigating, allowing for more time on task.

Results showed that single-users can benefit from a twenty-four monitor large, tiled high-resolution display and from curving it [31]. Therefore, the second experiment sought to determine why bringing all pixels into visible range improves performance and how. The research questions in the second experiment were:

1. Does the location of an object matter? Do users perform faster when targets are in certain regions of the display on either the flat or curved form?
2. Does the virtual distance, the distance between two objects on the screen, affect user performance differently on the two forms because the physical distance in the user's space changes?

3. Does the form of the display influence the level of detail of a user's insights?

The corresponding hypotheses were:

1. When locating detailed information (a target), users will perform faster on the curved display with no bias towards any region of the display, whereas, users will take longer to find targets in the outermost regions of the flat display (targets outside of their initial visual range).
2. Virtual distance will affect user performance more on the flat display. It will take a greater virtual distance before user performance drops on the curved display.
3. There will be a tradeoff of insight levels on the two forms. Users will gain more detailed insights on the curved display, and users will gain more overview insights on the flat display.

Chapter 3

Literature Review

The majority of research related to large high-resolution displays has been about the physical construction of the display [12, 18, 23, 25, 27] or the software and algorithms available for distributing the graphics [19, 32]. Less research has been done on the usefulness and usability of these displays.

Additionally, most research has been done on using these displays for collaboration [14, 22, 34] rather than for single-user applications. Multiple users may benefit from the flat display more because there would be more room to move. However, our focus is on quantifying the user performance benefits of larger, high-resolution displays for a single user. Curving the display is likely to be more practical and beneficial for single users.

3.1 Single-User Benefits

One common single-user scenario is using multiple monitors to expand the desktop. There are two paradigms for multiple monitor users, either the idea of partitioned spaces used as different rooms, or used as one large space [16]. People tend to use monitors to the left or right as separate rooms and monitors that are tiled vertically as single spaces [3]. There are many open issues with interaction, notification, and window management across multiple monitor desktops [1, 17, 20, 21].

Because our application is for geospatial analysis, we are more interested in the one large space paradigm. Research in this area has shown that large high-resolution displays can result in better performance than panning and zooming on smaller displays [4, 5], that larger displays improve performance even when the visual angle is maintained [35], and that using larger displays narrows the gender gap on spatial performance [11]. In addition, Focus+Context screens are an attempt to take advantage of lower resolutions for context, and a small high-resolution area for details [7]. This technique limits the user to virtual panning rather than physically moving. However, the highest total pixel-count display used in all these experiments was a modest 3×3 tiled monitor display with 3840×3072 total pixels. With this experiment, we go beyond those totals to much larger displays.

A concern when using a tiled display is the impact of the bezels. Mackinlay and Heer [24] suggested techniques of working around these issues. Other research suggests that discontinuities are only a problem when combined with an offset in depth [36]. However, in this work we do not address this particular issue; no information is hidden behind the bezels.

3.2 Reconfigurable Displays

One question that arises is whether or not there is a point of diminishing returns. For example, is there a point at which a wider field of view no longer increases user performance? Additionally, at what point are there so many pixels in a display that performance no longer increases? One method of decreasing the access cost is to curve the display so when users turn their heads the display is still at an equal distance from them (as described in section 5.1).

Curving displays can be challenging; to our knowledge, you cannot currently purchase a bendable LCD monitor. Dsharp is a display that uses multiple projectors in creating a curved display by carefully aligning the images [11, 33]. NASA's hyperwall allows monitors in a 7×7 tiled array to be tilted and rotated [28]. Also available are rear-projected blocks that can be stacked [30]. However, to the authors' knowledge, there is no empirical comparison of user performance between flat and curved displays.

3.3 Information Separation

It is common in work place environments for single users to have more than one display. In work done by Tan and Czerwinski, they evaluated the effect of separating information with wider viewing angles, and the effect of discontinuities of the displays themselves. In their experiment they used two types of displays at different distances and two visual angles. They found there was a detrimental effect on user performance when the information was separated by the larger visual angle and a larger distance [37]. While they did not find an effect for simply placing the information on the outside edges of two separate monitors, we feel that if they had increased the visual angle even farther they would have found a significant effect. For example, in our twenty-four monitor display, information can be separated by up to eight columns in width. We theorize that by placing data at the edges of this display will make it harder for the user to effectively compare the information.

3.4 Insight Based Evaluation

Traditional visualization methods and tools are evaluated by running controlled experiments, usability tests, metrics, heuristics, and models. The importance of running these studies is uncontested. However, it was argued by Saraiya et al. that it is also important to evaluate the types of insights users glean from using a visualization. They defined insight to mean an individual observation about the data, or a unit of discovery. In their evaluation of a bioinformatics visualization tool, they recorded what facts the users pointed out, as well as the "domain value," which indicated the importance of the insights the participants had. The researchers conclude that a visualization tool influences the interpretation of the data and insight gained by users [29].

Large, high-resolution displays have promising uses in the field of information visualization because of the increase in screen real estate. With more space and pixel density, there is a potential for displaying more data with greater context on large, high-resolution displays. We argue that when evaluating these displays it is important to use similar methods to those used in evaluating visualization tools, such as usability testing and controlled experiments. We also feel that the insights users glean from data displayed on these large displays may have different domain values or "degree of detail" depending on the size and form of the display.

3.5 Summary

In summary, this work builds on and extends previous research by considering single user performance on geospatial tasks using a larger, higher-resolution display than used in other experiments. Until now, the highest total pixel-count display used in all these experiments was a 3×3 tiled monitor display with 3840×3072 total pixels. This work also considers the user performance benefits of reconfiguring the display by uniformly curving it when other research considered only a curved display or only flat displays.

Chapter 4

Display

The display was made up of twenty-four seventeen inch LCD monitors and twelve GNU/Linux computers. Each monitor was set to its highest resolution of 1280×1024. Calibration was attempted by making simple adjustments with each monitor's controls, resulting in close, but not perfect, calibration. Each computer powered two monitors. We removed the plastic casing around each monitor to reduce the bezel size (gap) between monitors from 4cm to 2cm. We then mounted three monitors vertically on each reconfigurable wooden stand. Since users may experience slight neck strain when looking up for long periods of time, we designed our power desktop to be no more than three monitors high [2]. Therefore, most of the monitors were added to the width of the display, making it wider than it is tall. This produced an 8×3 matrix.

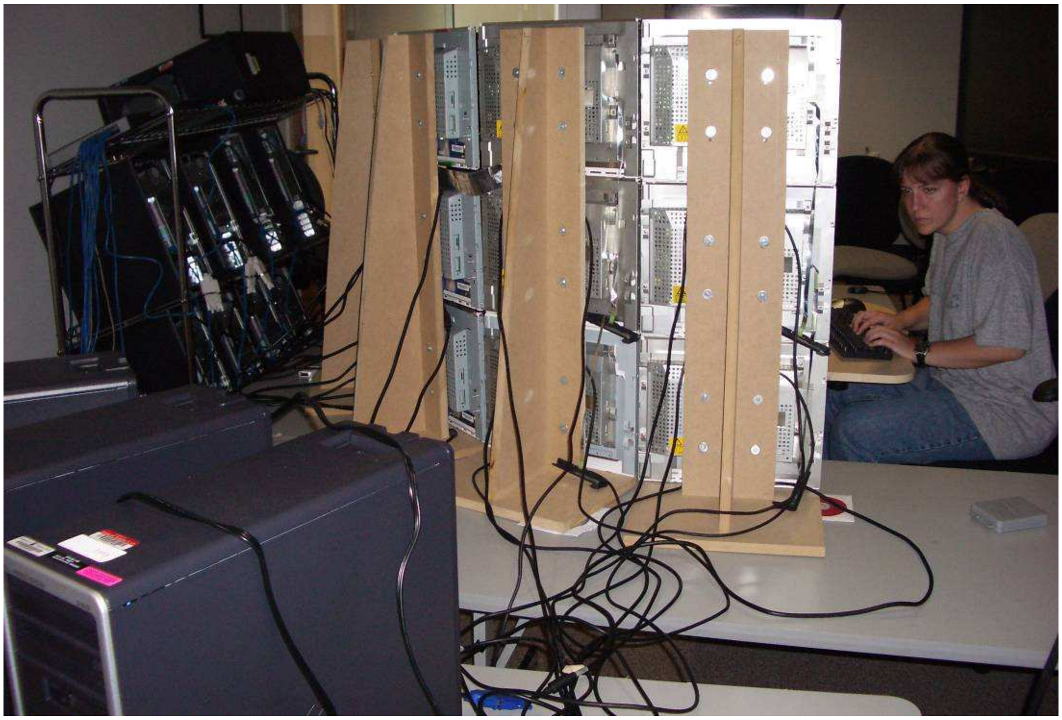

Figure 4.1: Cluster of twelve computers running the twenty-four monitor display

We networked the twelve GNU/Linux computers together in a private network using a gigabit switch (Figure 4.1). We then installed DMX (Distributed Multihead X) to create a unified display [13]. DMX is a proxy X server that provides multi-head support for multiple displays attached to different machines. When running DMX, the display appears to be one single GNU/Linux desktop that runs a standard window manager (e.g. KDE, GNOME, Fluxbox, etc.).

For the curvature variable in both experiments, we curved the display on the horizontal plane such that the monitors would uniformly face the user. To do this the columns were faced inward such that the angle between each column was equal. Thus, the display was part of a uniform circle. The following floor plan of our lab shows the display in both configurations (Figure 4.2). The display is shown with respect to the Vicon motion tracking cameras [26] used in the second experiment.

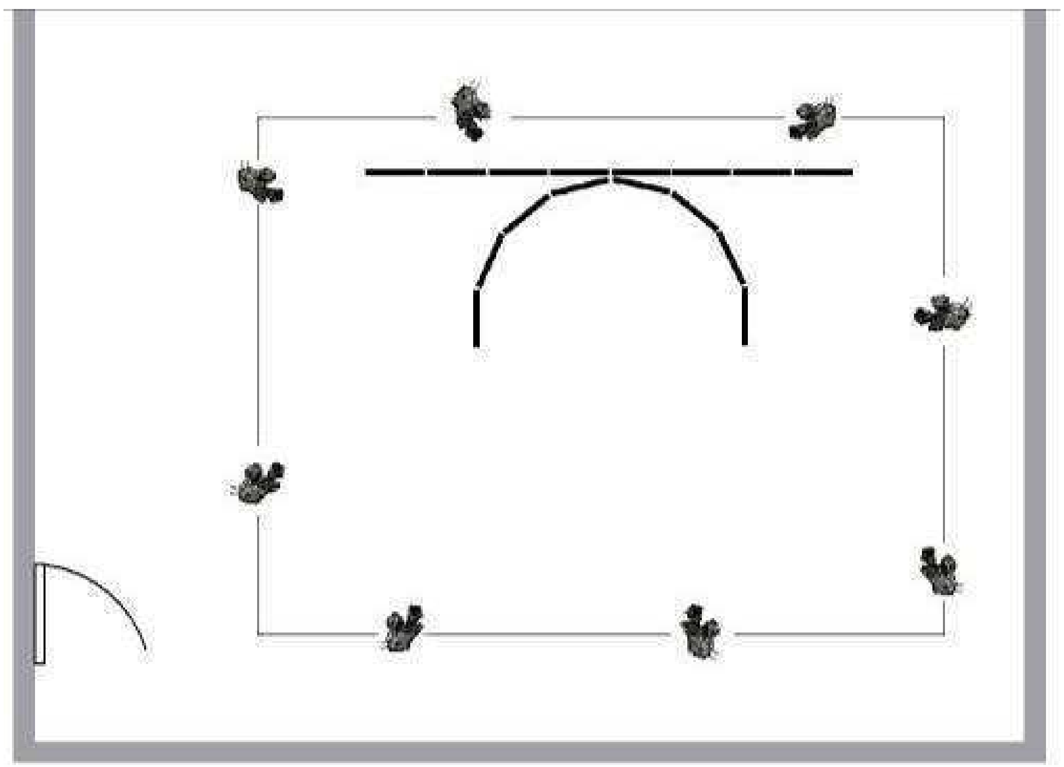

Figure 4.2: Floor plan of the display configurations with respect to the room and Vicon motion tracking infrared cameras

Chapter 5

Experiment 1: Viewport and Curvature

5.1 Motivation

Our motivation behind the experiment is twofold. First we wished to quantify the user performance benefits of increasingly larger displays (greater pixel-count) for geospatial tasks (Figure 5.1). We hypothesized that user performance would improve with larger displays because users would have more data and more context visible at once and because such displays afford efficiently navigating the information physically using eye, head, and body movement. However, counterarguments could be that such a large amount of visual information will overwhelm users, and that physical navigation will be too slow as compared to virtual navigation techniques such as pan and zoom. One could also argue that expanding the total screen size beyond the visual acuity of the eye wastes pixels.

Figure 5.1: Twenty-four monitor flat configuration

Our second goal was to determine if the curvature of such large displays affects user performance for geospatial tasks (Figure 5.2). Therefore, we also hypothesized that curving the display would decrease the amount of time spent physically navigating, allowing for more time on task. Users would only have to turn rather than walk to far away pixels. Our main motivation for curving the displays was not to find an optimal curvature but to see if there exist any benefits of curving a display compared to keeping it flat. Therefore, we chose the same radius for all curved conditions (Figure 5.3).

Figure 5.2: Twenty-four monitor curved configuration

The following is an analysis of the interaction between visual acuity and display curvature, demonstrating how curving a display brings pixels into visual range.

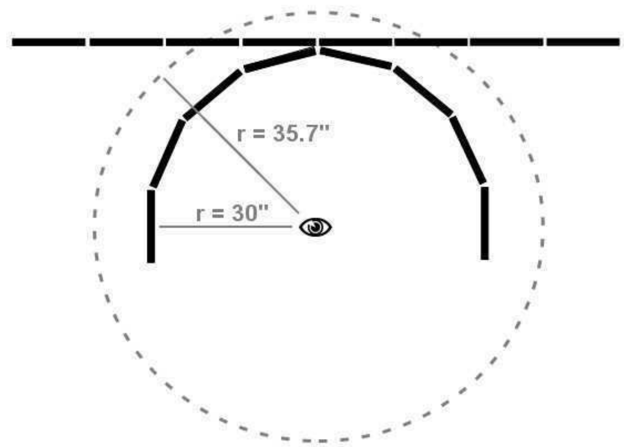

Figure 5.3: Visual acuity (dashed circle) and display configurations.

The display consisted of Dell 1740FPV color monitors that each had a maximum resolution of 1280×1024 and a dot pitch of 0.264mm×0.264mm. We calculated the maximum distance from which a user with normal visual acuity (20/20 vision) could resolve a 0.264mm pixel to be 90.7565cm or about 35.7 inches. This distance from the user is represented in Figure 5.3 by the dotted circle.

Consider the display curved. The maximum resolvable distance remains the same (35.7 inches). If all users had perfect vision and the display had a radius no more than 35.7 inches then all pixels are resolvable with only head and eye movements. In this experiment the display radius was set to a distance (30 inches) to accommodate slightly worse than 20/20 vision. Therefore, the entire width of our curved display (10,240 pixels wide) is resolvable. This is 2.75 times more resolvable pixels than with the flat condition. In general, one can create different curvatures by adjusting the radius. This curvature places the outermost columns facing each other, 180 degrees apart.

Now consider what happens when the display is flat. The maximum number of pixels that can be resolved on a flat display with only head and eye movements occurs when the user is standing unrealistically close to the display and looks to the left and to the right (setting aside the problem of the viewing angle). This means the maximum display width at which all pixels are resolvable is 90.7cm×2 = 181.5cm (71.5 inches) or 6,875 pixels wide. Realistically, the user will not be standing directly against the display and as the user moves back fewer pixels will be resolvable. If the user is 30 inches from the center of the display, as they started in this experiment, then the number of resolvable pixels with only head and eye movements is 3,723. This is represented in Figure 5.3 by the intersections between the dotted circle and the eight straight blocks representing the flat display.

5.2 Method

5.2.1 Hardware and Software Used

We used a modified version of the NCSA TerraServer Blaster, an open-source application that Paul Rajlich from NCSA (National Center for Supercomputing Applications) wrote for visualizing imagery from the national TerraServer database using Chromium [8]. Chromium is an open-source application that uses real-time parallel rendering of OpenGL.

We modified the NCSA TerraServer Blaster application in a variety of ways. First, we modified the application by increasing its download and caching efficiency. Second, we modified the application by adding direct keyboard and mouse input; previously the application only ran from a console window.

All users were given a standard keyboard and mouse. The keyboard stand had wheels for easy mobility and was used across all conditions. Users could virtually navigate (pan and zoom) using the keyboard. Virtual navigation in this work is defined to be navigating the interface using indirect manipulation provided by the hardware and software (i.e. clicking a key causes the screen view to change). Conversely, physical navigation in this work is defined to be navigating the interface using body movements (i.e. moving such that the new position and orientation provide a different view). The arrow keys controlled virtual panning such that it seemed to move the user in that direction (egocentric view), moving the image in the opposite direction. Users could smoothly zoom with the plus (+) and minus keys (-). Users could also quickly zoom by one scale using the Page Up and Page Down keys. The space bar key corresponded to a hotspot that restored the user to the same scale and coordinate as the starting view for that task. The mouse was provided for the route tracing and comparison tasks, allowing users to draw check marks at the same coordinate and scale of the participant's mouse click. Users were familiar with the keyboard and mousecommands by the end of the tutorial.

5.2.2 Experimental Design

The independent variables were viewport size, curvature, task type, and task difficulty. We chose three viewport sizes: one monitor, twelve monitors, and twenty-four monitors. For the one monitor condition the TerraServer application was simply resized to fit one of the middle monitors. For the twelve monitor condition the application was expanded to half of the display such that it filled a 4×3 matrix of monitors. For the curvature variable, we chose two curvatures: flat and a curved with radius equal to 30 inches (Figure 5.3). We tested five of the six conditions (Table 5.1). The one monitor curved condition is not applicable since one cannot curve a single monitor.

	Flat	*Curved*
1 monitor	✓	
12 monitors	✓	✓
24 monitors	✓	✓

Table 5.1: Five conditions evaluated in experiment 1

Viewport size and curvature were between-subject variables because of the time it takes to reconfigure the display. The order of tasks within each task type was counterbalanced using two 4×4 Latin Square designs, where one dimension represented the task type and the other dimension represented four of the eight participants. Each task type had one easy and one hard task. Within each task type (e.g. the two search tasks), half of the participants would get the easy task first and the other half would get the harder task first.

For each condition, we used eight participants for a total of forty participants. All participants were undergraduate or graduate students. The majority of the participants were computer science majors with a few exceptions. The average age of the participants was twenty-five with a range between twenty-one and thirty-one years old. Twenty-seven of the participants were male and thirteen were female. All participants had normal to corrected-normal vision and reported having daily use with computers. Users were not expected to have a background in geography and the tutorial covered the background necessary to complete the tasks.

5.2.3 Tasks

The experiment used a range of geospatial typical of aerial imagery comparison and analysis. Geospatial data is ideal for this experiment because it is naturally a high-resolution, multi-scale, and dense data set. This type of data is also useful to many people, including those in the intelligence community.

We chose three different task types for all conditions: search, route tracing, and image comparison. We chose search and route tracing tasks based on previous research in geospatial data on larger displays [5]. We chose an image comparison task based on expert geographer and cartographer advice. Participants performed two of each task type, an easy and a hard task, for a total of six tasks per condition. All tasks involved navigating extremely large aerial images at multiple scales. The starting extent, or ground distance shown, was held constant for all viewport conditions. Therefore, the starting scale of each task was different for each viewport size to display the same extent.

Search tasks involved locating a specific unaltered object in the aerial view. The easy search task involved finding the "14R" label at the end of a Chicago airport runway (Figure 5.4).

Figure 5.4: Easy search task for "14R" label on the flat twenty-four monitor condition

The hard search task involved searching all of the Chicago area for a red bull's eye on the roof of a building (Figure 5.5). The bull's eye task was more difficult because the search area (extent) was greater. Participants were told to point to the object when they found it so that the proctor could visually verify the answer (dependant variables are time and accuracy).

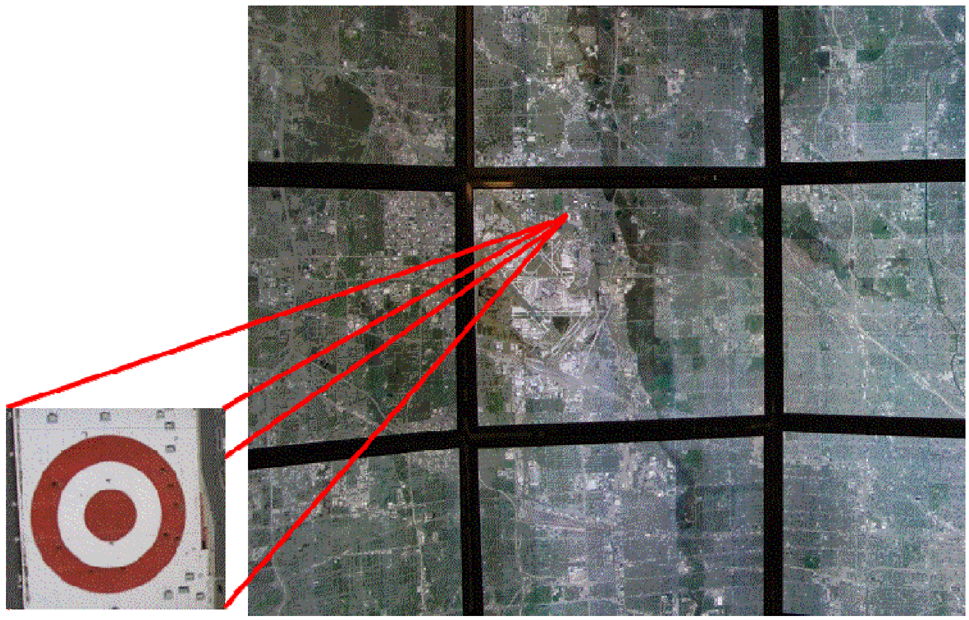

Figure 5.5: Hard search task for a red bull's eye on the curved twenty-four monitor condition

For the route tracing tasks, users followed a given route, marking underpasses/overpasses along the route. A green arrow and red octagon icon indicated the start and stop points on the route, and fictitious highway icons were added along the route for guidance (Figure 5.7). Users could mark checks anywhere on the imagery with the mouse. The instructions were to mark all underpasses/overpasses along the route and inform the proctor when complete (dependant variables are time and accuracy).

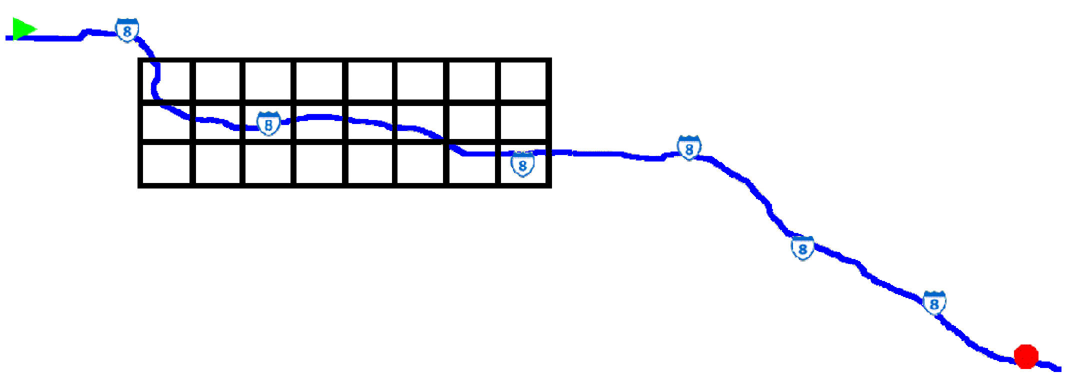

Figure 5.6: The easy route tracing task with respect to the twenty-four monitor display at a frequently zoomed scale

The easy task was to mark underpasses along a portion of Expressway 402 East of Atlanta, GA (labeled Highway 8) (Figure 5.6). The hard task was to mark overpasses along a portion of Highway 60 in Los Angeles, CA (labeled Highway 63) (Figure 5.7). Overpasses were more difficult because identifying a road underneath the route requires a closer inspection; whereas, with the underpasses, roads crossing over the route stand out.

Figure 5.7: Route tracing task on the curved 24 monitor condition

In the image comparison task users could toggle between two aerial views (Figure 5.8). One view was an older 1988 black and white view of the area using DOQ (Digital Orthographic Quads) imagery, and the other was a recent 2003 color view. Superimposed on the views was a 30×15 grid. The task was to identify blocks in the grid where there were urban changes. For example, an urban change is where there are new buildings, destruction of old buildings, new roads, etc. Subjects were not to include natural phenomena such as trees or lakes. Users could click on blocks to mark a check, signifying a change. Users had fives minutes to check as many blocks on the grid that had urban changes (dependant variable is accuracy).

Figure 5.8: Image comparison task

5.2.4 Procedure

Each user took about one hour to complete the experiment. The tasks took no longer than five minutes each as there was a timeout at five minutes to reduce fatigue.

Before beginning the experiment, participants were asked to fill out a demographic questionnaire as well as inform the proctor of any physical conditions such as color-blindness or claustrophobia. Participants had a training session on how to use the program before beginning the experiment. The tutorial covered the buttons used for keyboard navigation. Users were told that they were allowed to physically move around, and were given a stool and rolling keyboard stand. Regardless of the viewport size, users began sitting at the center of the viewport on the stool with the keyboard and stand in front of them.

Users were given written instructions for each task on a piece of paper and were encouraged to ask for any clarification before beginning. Instructions were to perform as quickly and accurately as possible. Then the experiment began.

After every task type (i.e. after both search tasks), participants were asked to complete the NASA Task Load Index (NASA-TLX) rating workload for both tasks.

5.3 Results

5.3.1 Completion Times

Task completion time was measured for both the route tracing and search tasks. Times for participants that timed out after five minutes were recorded as five minute task completion times. This ensures that the results are not skewed to only consider quick performers. One participant was thrown out as an outlier, since that participant was the only participant to time out on every task, regardless of difficulty level. For the comparison tasks participants were always given five minutes, therefore completion times for the comparison tasks were not analyzed.

5.3.1.1 Overall Completion Times

To include the one monitor condition, we performed a 3-way analysis of variance (ANOVA). There was a main effect for display configuration ($F(4,136)=3.52$, $p=0.009$), task type ($F1,136)=134.9$, $p<0.001$), and task difficulty ($F(1,136)=15.39$, $p<0.001$). Search tasks were significantly faster than route tracing tasks and easy tasks were significantly faster than hard tasks. Post-hoc analysis of the display configurations showed a statistically significant difference ($p<.05$) between several of the display configurations.

Figure 5.9 shows the results of the post-hoc analysis. Non-overlapping confidence intervals are statistically significant at the alpha level of 0.05. All large display conditions, except for the twelve flat condition, are statistically faster than the one monitor condition. Furthermore, the twenty-four curved condition is faster than the twelve flat condition.

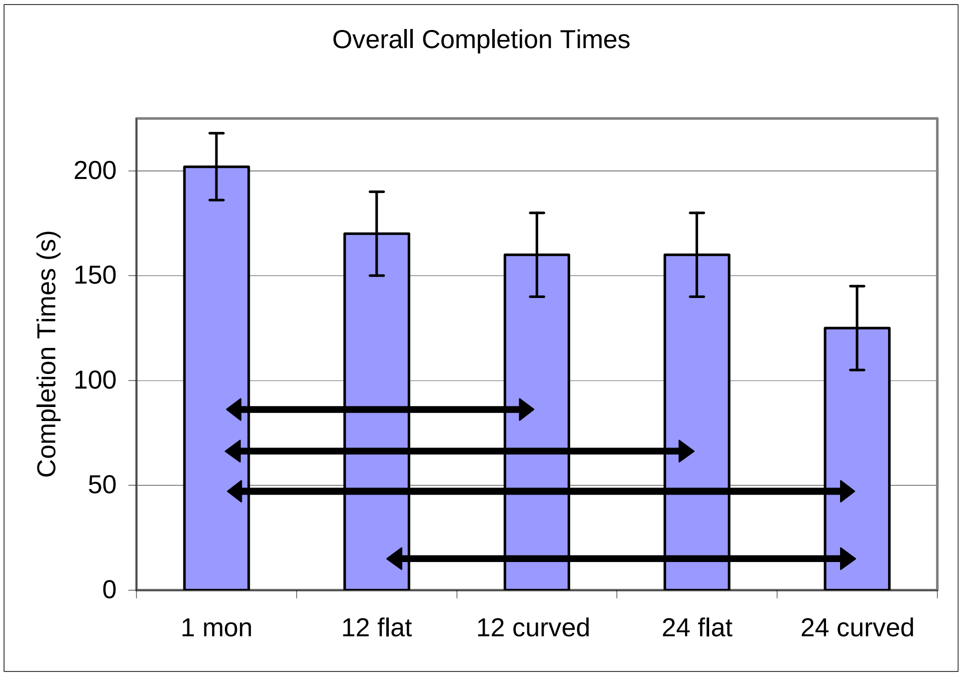

Figure 5.9: Performance times (s) of all display configurations. Non-overlapping error bars indicate statistical significance (significantly different conditions also linked by arrows).

Figure 5.9 shows the general trend that increasingly larger viewport sizes and curved displays reduce performance time. An interesting observation is that by curving the twelve monitor condition (158.5s) the performance times roughly equated to that of the twenty-four flat condition (158.3s). Yet, by curving the twenty-four monitors the performance time again decreased (124s).

5.3.1.2 Task Specific Completion Times

Since, 48% of participants for the hard route task and 26% of the hard search task timed out regardless of the display condition, the hard tasks had no significant results. This section only shows the results for the easy tasks.

As the experimental design was an incomplete factorial design (Table 5.1) we analyzed the easy tasks by performing two different analyses of variance. The first analysis was a mixed-model three-way ANOVA in which the curvature and viewport size were between subject and the task type was a within subject factor. Note, here task difficulty is eliminated as a factor because hard tasks are not analyzed. This first ANOVA did not include the one monitor condition, because it is not relevant to the curvature variable.

The resulting analysis showed that there were main effects for viewport size, curvature, and task type. There was also an interaction between the task type and viewport size ($F(1,27)=10.26$, $p=0.003$). For viewport size, we found that participants performed faster on the twenty-four monitors (112 seconds) than the twelve monitors (145 seconds) ($F(1,27)=7.18$, $p=0.012$). For curvature we found participants performed faster on the curved displays (111 seconds) than the flat displays (146 seconds) ($F(1,27)=7.82$, $p=0.009$) (Figure 5.10).

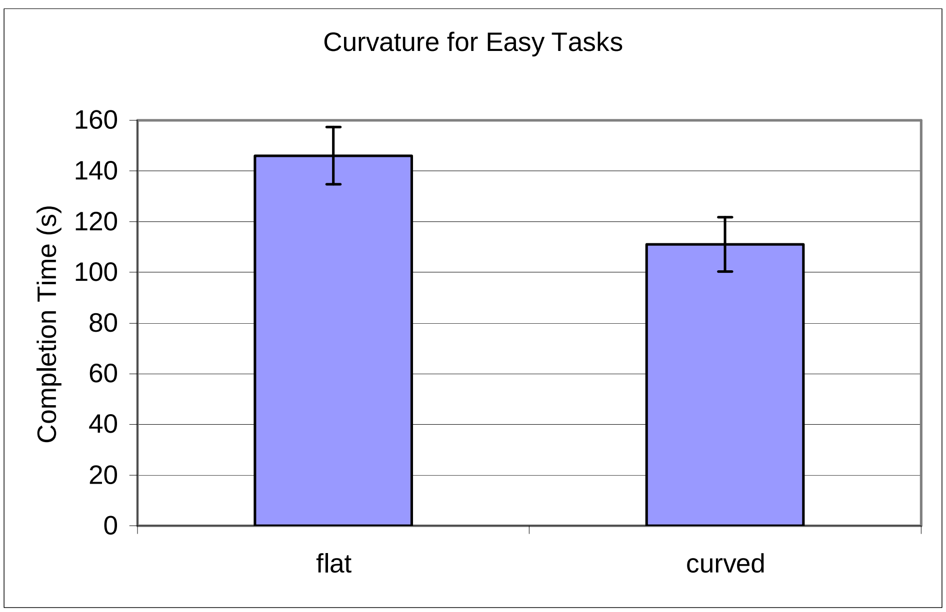

Figure 5.10: Average completion times for easy tasks on twelve and twenty-four monitor curvature conditions

Lastly, for the task type we found that that the search tasks were faster than route tasks ($F(1,27)=186.1$, $p<0.01$).

We used Fisher's protected t-test as a post-hoc comparison to further investigate the viewport size and task type interaction. For the route task we found that the twenty-four monitors (178 seconds) were faster than the twelve monitors (251 seconds), whether flat or curved (p=0.004). For the search task showed that the twenty-four monitors (46 seconds) was not statistically different than twelve monitors (38 seconds) (p=0.58) (Figure 5.11). This only means that there may not be a difference in search performance between twelve and twenty-four monitors. However, there is a benefit of either large viewport size over one monitor (seen next).

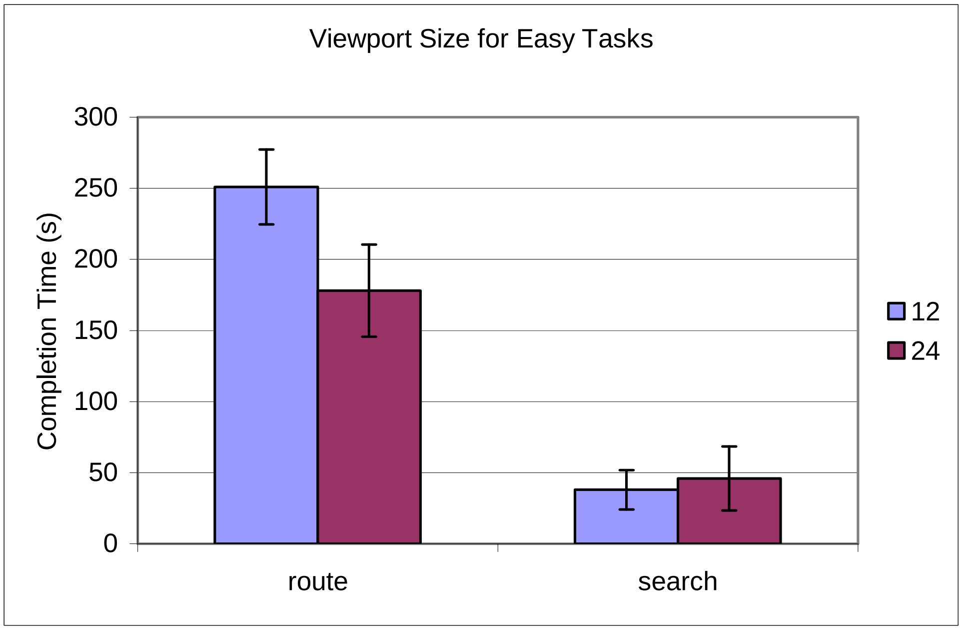

Figure 5.11: Average completion times for easy search and route tasks on twelve and twenty-four monitor viewport sizes

The second analysis was a mixed design two-way ANOVA that took into account the one monitor condition; the variables were display configuration (i.e. one monitor, twelve flat, twelve curved, 24 flat, and 24 curved) and task type (i.e. easy route and easy search). The result was an interaction between the task type and display configuration (F(4,34)=4.24, p=0.007).

Post-hoc one-way ANOVAs showed that both the search task (F(4,34)=4.03, p=0.009) and the route task were statistically significant (F(4,34)=3.84, p=0.01). Protected t-test results for the search task show that the twelve flat, twelve curved, and twenty-four curved conditions were statistically faster than the one monitor condition, and the twenty-four curved condition was statistically faster than the twenty-four flat condition with $p<0.05$ (Figure 5.12). The same test for the route task shows that twenty-four curved is statistically faster than twelve curved and twelve flat with $p<0.05$ (Figure 5.13).

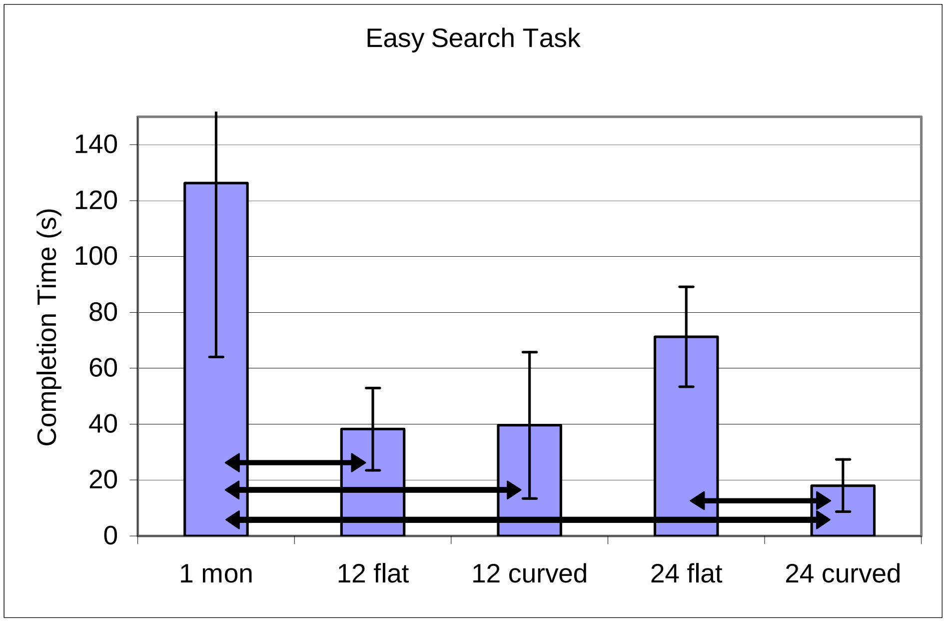

Figure 5.12: Performance times for the easy search task for all display configurations. Non-overlapping error bars indicate statistical significance (significantly different conditions also linked by arrows).

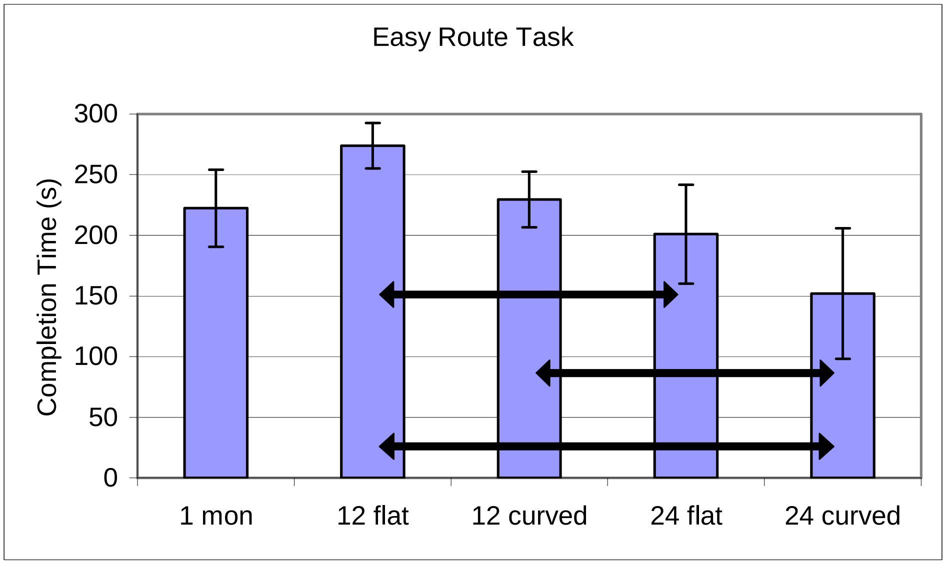

Figure 5.13: Performance times for the easy route task for all display configurations. Non-overlapping error bars indicate statistical significance (significantly different conditions also linked by arrows).

In summary, we did not find an interaction between curvature and viewport size. However, we did find an interaction between viewport size and task type. This indicates that curvature helped with performance times regardless of viewport size and that viewport size helped more with the route task than the search task.

This difference between tasks could be explained due to the nature of the tasks themselves. The route task was very long and utilized the wide screen space, whereas the search task involved a square area, fitting more easily in the twelve monitor display with little zooming.

5.3.2 Accuracy

Search task accuracy was recorded as either 100% (1) or 0% (0) since participants either did or did not find the target within five minutes. For the route tracing tasks accuracy was recorded as the number of underpasses or overpasses that the participant marked compared to the actual number of under or overpasses. For example, if a person marked fourteen underpasses, their accuracy was 14 / 24 = 0.5 or 50%. Comparison tasks were recorded as the total number of squares marked on the grid by each participant. For both route tracing and comparison tasks, the marks were not evaluated as right or wrong marks. Because analysis of the imagery is subjective, all marks were included in the accuracy ratio.

Similar analysis as section 5.1.2 was performed with accuracy. A three-way ANOVA looking specifically at viewport size and curvature found a main effect of task type ($F(3,81)=43.57$, $p<0.01$). Similarly, a two-way ANOVA that took the one monitor condition into account also found a main effect of task type ($F(3,102)=55.77$, $p<0.001$). In other words, the accuracy of the tasks themselves were different, but the different display conditions did not have an effect.

5.3.3 Mental Workload

Mental workload was measured using the NASA Task Load Index. Four scales, mental demand, physical demand, effort and frustration were each measured on a scale from 0-100 where 100 was high and 0 was a low rating for that factor.

Using analysis of variance and followed by post-hoc analysis, the only statistically significant difference was on the level of frustration reported by users. Participants using one monitor reported significantly higher frustration levels than participants on all but the twelve flat condition ($p<.05$).

The lack of significant difference in the other three scales (mental demand, physical demand, and effort) may be due to the wording of the corresponding survey questions. Several of the subjects indicated that they were confused by those questions.

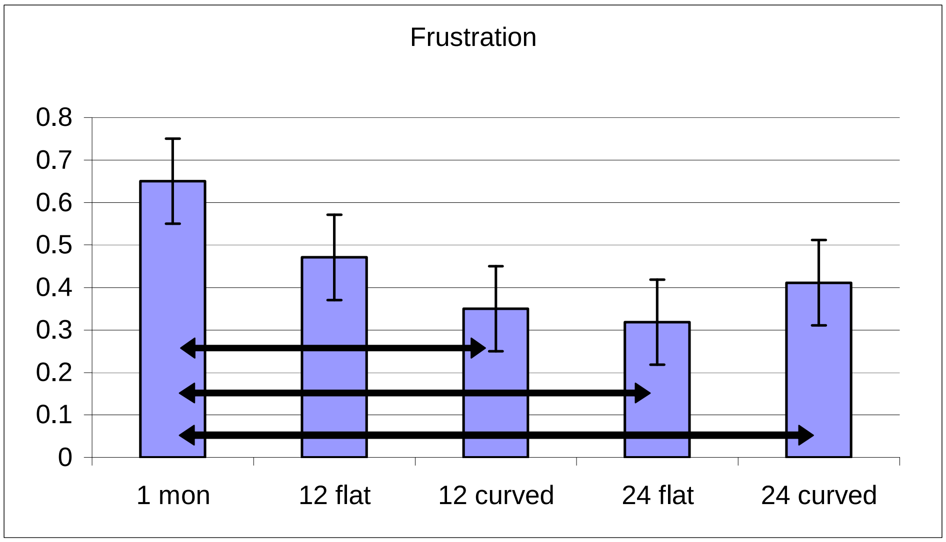

Figure 5.14: Frustration averages for all display configurations. Non-overlapping error bars indicate statistical significance (significantly different conditions also linked by arrows).

5.3.4 Observations

In general, we observed differences in how users interacted in the different conditions. First considering the viewport size, there was a striking difference between the one monitor condition and the larger display conditions. In the one monitor condition users tended to use more virtual navigation than those in the flat twelve and twenty-four monitor conditions. Specifically, users zoomed in and out significantly more on the one monitor condition to regain their overview of the task area. In the larger display sizes users tended to use more physical navigation. This included standing up, walking, leaning towards the sides of the display, and head turning. Often the user's strategy for accomplishing the task was the same (e.g. serial searching), but the technique was applied with virtual navigation in the one monitor configuration and with physical navigation in the larger configurations.

In the twelve and twenty-four monitor conditions, many users would adjust their technique for their second task of the same task type. For example, in the first image comparison task users would often search serially, but for the second task they would get an overview of the area looking for obvious changes before zooming in to compare details.

Considering curvature, users physically interacted with the largest displays in different ways. For example, on the flat twenty-four monitor condition more users would either stand or walk; in that condition, five out of eight users stood up at least once. In the curved twenty-four monitor condition, however, users would turn their heads or their body. It may be because of this change in physical navigation that performance times were faster when the display was curved.

Even though the twenty-four monitor display was physically large, most participants did not stray far from their stool, despite clear instructions during the tutorial that they may feel free to move around. One possible explanation is that participants could only interact with the keyboard and mouse, and if participants moved away from their seat then they would have to either move back to the keyboard or move the rolling stand with them. Although the wheeled stand provided in this experiment brought mobility to the keyboard and mouse, it is clear that there may be a need for alternate input devices.

Furthermore, users changed their area of focus less frequently on the flat twenty-four monitor condition than those on the curved twenty-four monitor condition. Often users on the flat display would focus on nine or twelve monitors at a time. Sometimes their focus area would shift from the left side of the display to the right side of the display over the course of the task. However, most users preferred to sit (even if they stood at some point) and use the center of the display as their focus area. On the curved condition users would switch their area of focus more often by a quick turn of the head. Therefore, it appears that curving the display results in the users making use of a greater percentage of the available pixels more frequently.

5.4 Conclusions

In the first experiment, we compare viewport size and curvature of large, high-resolution (96 DPI), high-pixel-count (up to approximately 32 million pixels) displays for realistic image analysis tasks. The primary contributions include the following:

In general, increased viewport size improves user performance, but it is task dependent. Overall, the larger display sizes improved performance over smaller sizes. On search tasks, both the twelve and twenty-four monitor conditions improve performance over one monitor, and were approximately 2-6 times faster. For route tasks, the twenty-four monitor condition improves performance over the twelve monitor condition and was approximately 50% faster.

The nature of the task and data is related to the viewport size in complex ways. The route task was very large data, but somewhat linear and horizontal (Figure 5.6). The large and wide twenty-four monitor display probably correlated well with the size and shape of the task data. Also, its linear structure was easy for users to virtually navigate, even with the small one-monitor screen.

Whereas, the search task data was square in shape and not as large in size (Figure 5.4), and required full 2D navigation of the entire space. Hence, the larger display sizes had the advantage of minimal virtual navigation, while the one monitor screen size required a lot of complex virtual panning and zooming. The twelve and twenty-four monitor display sizes probably had similar performance due to the square shape of the data, which did not need to take advantage of the wide aspect ratio of the twenty-four monitor display. The observed reduction in virtual navigation and increase in physical navigation correlates to improved user performance. Combining increased visual imagery with physical navigation was beneficial in this case.

Curved displays improve performance over flat displays regardless of viewport size. For the easy tasks, curvature performance was approximately 30% faster than flat. Of all five display conditions, user performance was the best on the curved twenty-four monitor condition. Curvature improved performance probably because users could better utilize the left and right outermost pixels on the display (as shown in section 5.1). In the flat twenty-four monitor condition, for example, users were at least 4 feet away from the furthest pixels. However, in the curved twenty-four monitor condition the user was never more than 2.5 feet from any given pixel.

Physical navigation changes from standing and walking to turning when the display is curved. We observed that the physical navigation was different on the flat and curved conditions. The change from standing and walking around the flat display to turning within the curved display supports our visual acuity hypothesis and that the deferent physical navigation was more efficient for users, better enabling them to visually access and process the imagery.

We also found that user frustration is significantly lower on the larger displays than on the one monitor condition. This might correspond to the greater use of human visual capacity and more natural physical navigation that reduces potential frustrations of virtual navigation.

Chapter 6

Experiment 2: Spatial Arrangement & Insights on Curved Displays

6.1 Motivation

In the previous experiment, we found that single-users could benefit from using our large, tiled high-resolution display (Figure 6.1). The research also shows that curving a large high-resolution display improves user performance as all the pixels are brought into visible range, changing the physical navigation necessary to complete tasks (Figure 6.2) [31]. However, it is beneficial to understand further why users perform faster on curved displays. Understanding this form's advantages can help us create guidelines for future display technologies of similar magnitude and resolution.

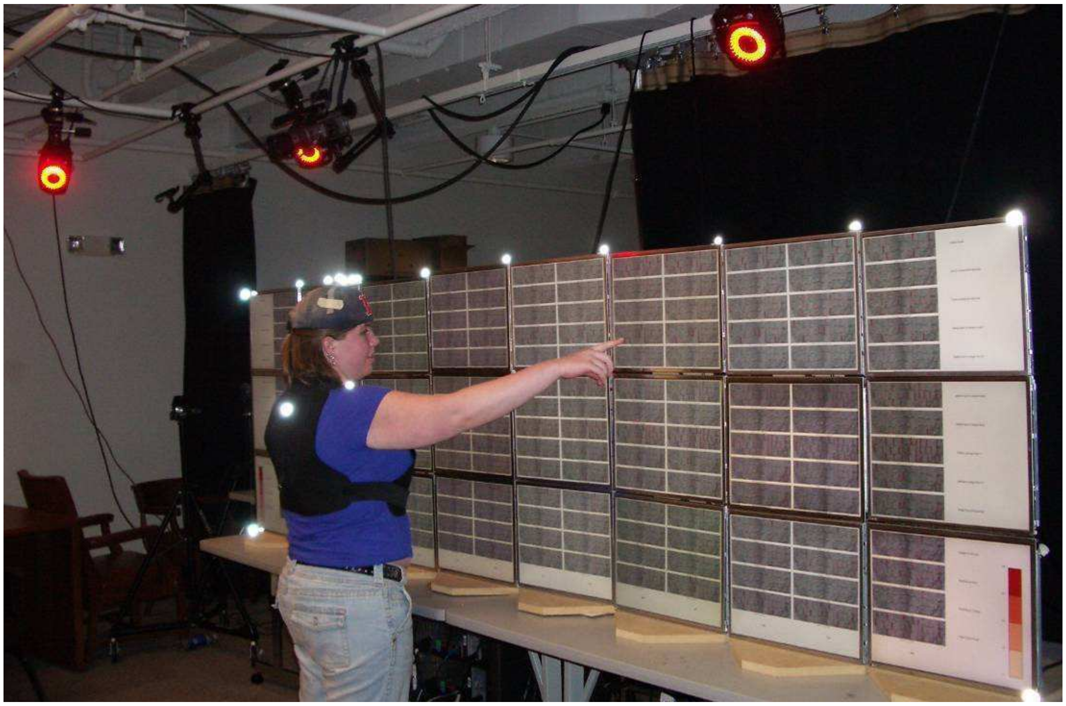

Figure 6.1: Twenty-four monitor flat configuration

In this study, we were trying to determine why bringing all pixels into visible range improves performance and how. Does curving the display improve performance because the position of the details no longer matters? Does curving the display allow users to compare virtually far apart objects faster because they are physically closer? Furthermore, since users have all the pixels (essentially all the details) available at once, is there is a tradeoff of an insight’s degree of detail (the amount of data that corresponds to the observation) on the two forms?

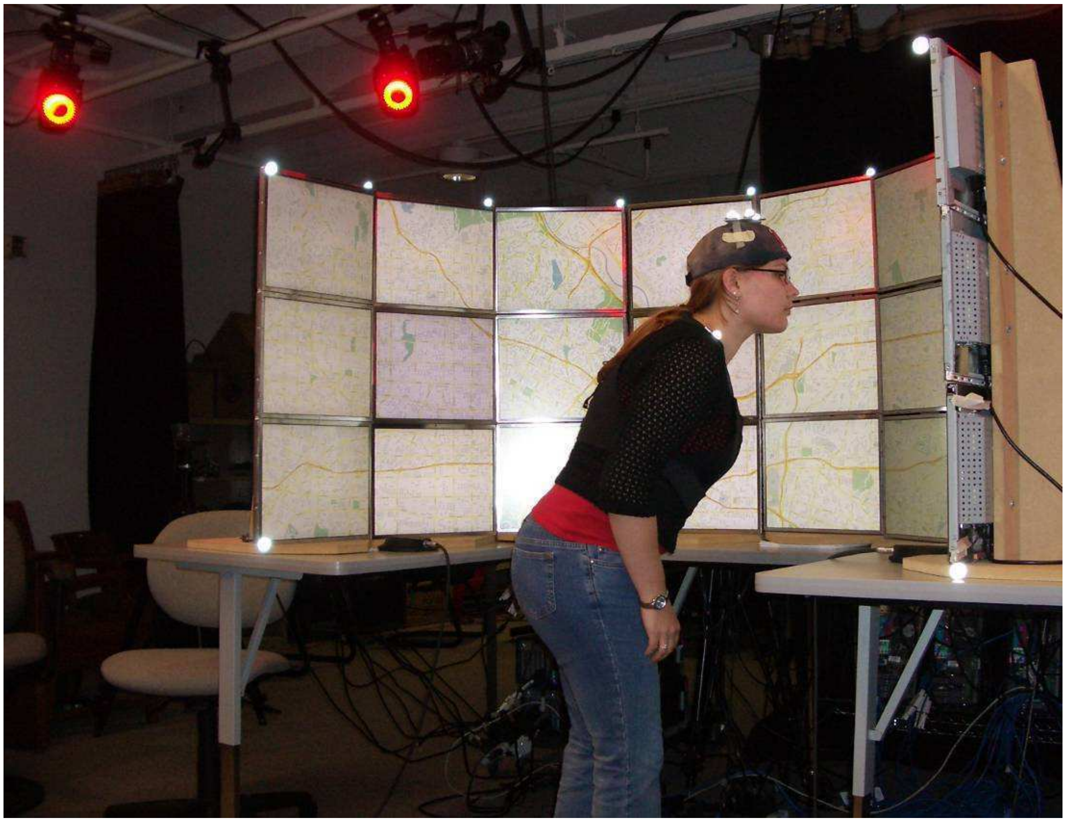

Figure 6.2: Twenty-four monitor curved configuration

Tasks used to evaluate participant performance are traditionally directed towards a predetermined answer. This makes it relatively easy for researchers to determine user performance on tasks. However, as illustrated by Saraiya et al. it is equally important to understand the types of observations and insights users can gain from visualizations [29]. We believe that insight-based evaluation should also be considered when evaluating the form factor of large, high-resolution displays.

Therefore, our motivation in conducting this experiment is threefold. First, determine how much the position of a detail affects user performance on the two forms. Second, determine how much the virtual distance between data affects user performance on the two forms. Third, determine if the form of the display affects the degree of detail of insights users gain from visualizations.

We hypothesize that when locating detailed information (a target), users will perform faster on the curved display with no bias towards any region of the display, whereas, users will take longer to find targets in the outermost regions of the flat display (targets outside of their initial visual range). Also, we hypothesize that virtual distance (the distance between two objects along the screen) will affect user performance more on the flat display. It will take a greater virtual distance before user performance drops on the curved display. Lastly, we hypothesize that there will be a tradeoff of the degree of detail of insights on the two forms. Users will gain more detailed insights on the curved display, and users will gain more overviewed insights on the flat display (further defined in section 6.2.3).

6.2 Method

6.2.1 Hardware and Software Used

For both forms, we raised the display to suit standing users. In order to track and capture their chosen movements, users were not given a seat during tasks. The bottom of the display was about three feet (36.5 inches) off the ground, and the top of the display was about six feet (71 inches) off the ground. Also to allow for free movement, no input devices were provided; all tasks involved static images.

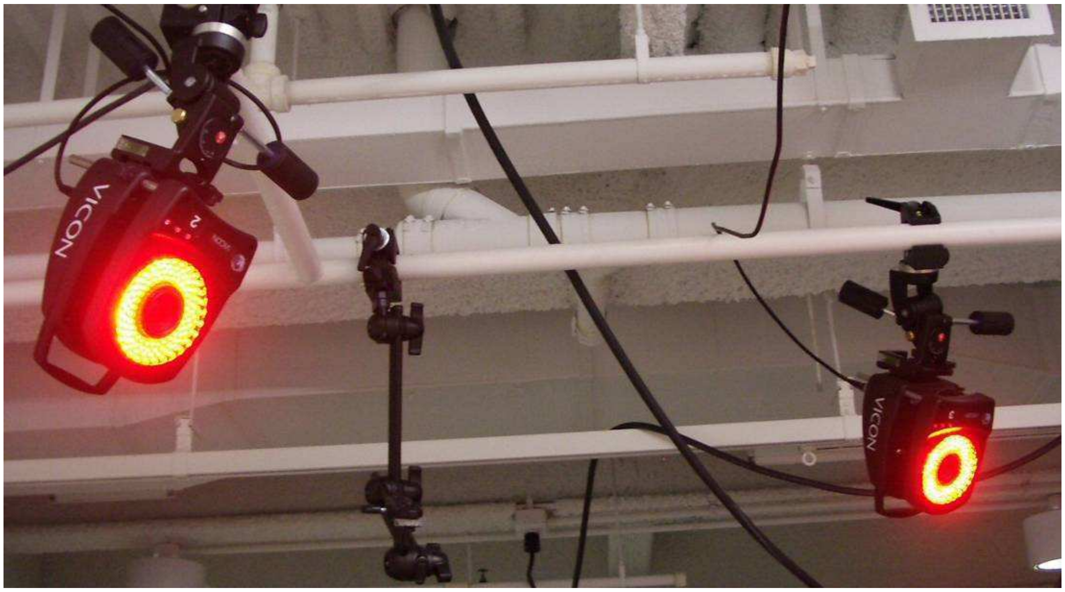

Figure 6.3: Vicon motion tracking infrared cameras

All users were given a vest and hat to wear with reflective markers for the Vicon motion tracking system (Figure 6.3). The Vicon system allowed us to track the user's position and orientation. Reflective markers can be grouped to signify one object in the motion tracking system. All the markers on the vest were grouped to track the position and orientation of the person's upper body and the markers on the hat were grouped to track the position and orientation of the person's head. At each timestamp, six numbers were recorded for both objects. The first three numbers were the coordinates (position along the x, y, and z axes) of the object. Using these numbers, we were able to measure the Euclidean distances moved in 3D space. The second three numbers were the angles of the object with respect to the x, y, and z axes. This was used to quantify the amount of turning.

6.2.2 Experimental Design

The experiment design examined two factors: form and task type. Form is a two level factor (Figure 5.3), and task type is a three level factor. Below is the full factorial design tested (Table 6.1).

Form	Task Type
Flat	Search
	Comparison
	Observation
Curved	Search
	Comparison
	Observation

Table 6.1: Six conditions evaluated in experiment 2

Each task type tests one of the three hypotheses stated above. Therefore, each has a different design. The search tasks covered seven regions of the display. For each form, participants had two search tasks in each region. Regions are defined by columns (Figure 6.4).

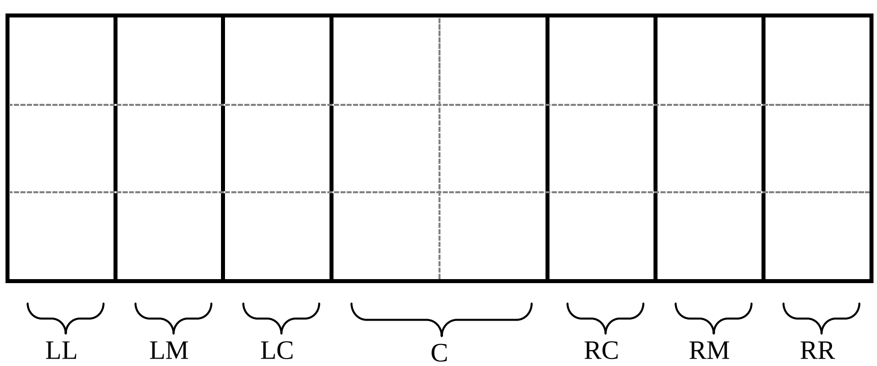

Figure 6.4: Defined regions for the search tasks

The comparison tasks covered seven virtual distances of the display. For each form, participants had two comparison tasks for each virtual distance. Virtual distances were defined by how many columns apart the two data values were to compare (Figure 6.5).

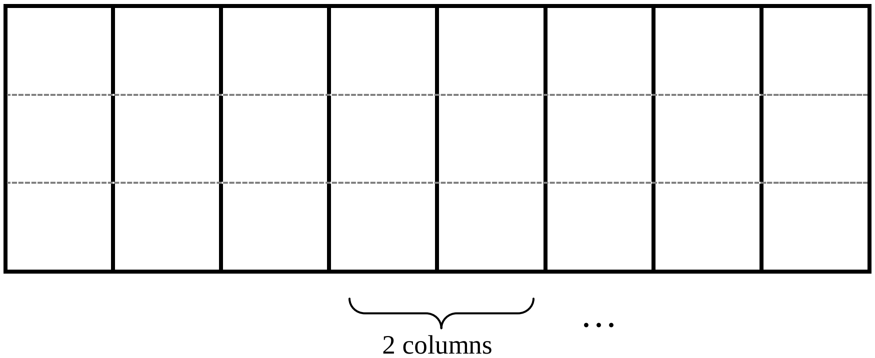

Figure 6.5: Defined virtual distances for the comparison tasks

All independent variables were within-subject. There were sixteen participants total. Each participant came for two sessions, one with the display flat and one when curved. Half of the participants had the display flat first, and the other half started with the display curved to counterbalance learning effects. For motivation, all participants were paid $5, and those with the best average performance on any task types won a $40 prize. Within each task type, the order was randomized. Each session followed the following task type order: insight, seven alternating search and comparisons, insight, seven alternating search and comparisons, and insight.

Six participants were graduate students, six participants were undergraduate students, and four participants were professionals. All of the students were in engineering: five computer science, two mechanical engineers, one computer engineer, and one electrical engineer. The average age of the participants was twenty-four with a range between twenty and thirty years old. Eleven of the participants were male and five were female. Eleven participants had corrected vision: seven with glasses, three with contacts, and one with corrective eye surgery. All participants reported having at least daily use with computers; fourteen reported as much as hourly use.

6.2.3 Tasks

We chose three different task types for all conditions: search, comparison, and insight. All task images were static, requiring no virtual navigation (panning and zooming).

For the search tasks, users were given a static street map, constructed from Google™ maps, each with a single gray tower embedded. Participants were asked to locate the gray tower (Figure 6.6). The search tasks were designed so that the water tower would appear in different regions of the display, so we could record user performance with respect to where the target was located.

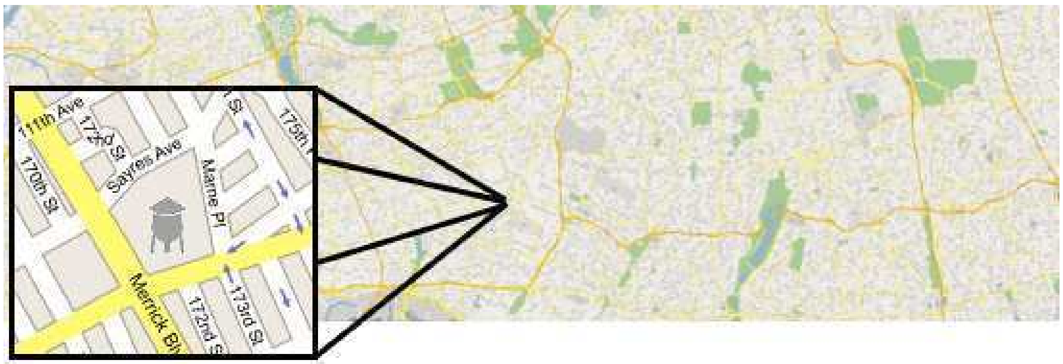

Figure 6.6: Example search task in experiment 2

In both the comparison and insight tasks, users were given a visualization of the percentage of multiple demographic groups across the United States over fourteen years (Figure 6.7).

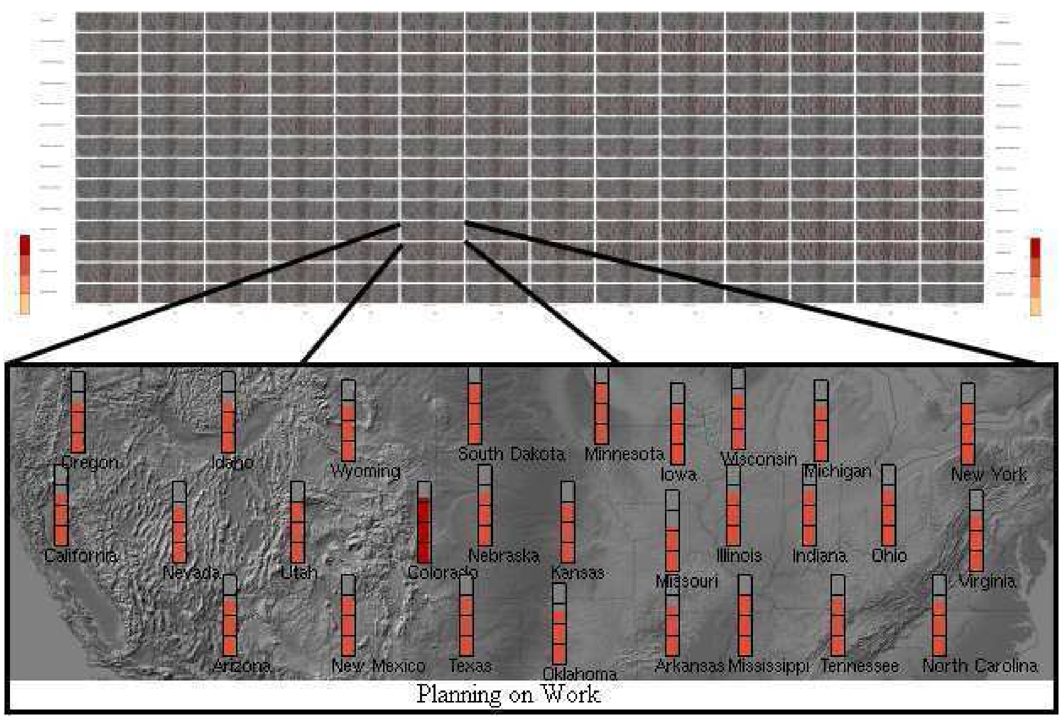

Figure 6.7: Visualization for comparison and insight tasks in experiment 2

The visualization is one of Yost's multiple view designs with additional demographic labels added on the right and along each row to reduce the navigation necessary for reading the labels [38]. The data values were fictitiously generated from semi-random numbers to include everything from trends to anomalies in the data. We did not use real data so that we could create multiple instances of the visualization for repeated measures. Demographic labels were embedded on the left, right, and along each row below the corresponding map to reduce any effects of the virtual distance of labels as seen in Figure 6.7.

For comparison tasks, users were given two specific values to compare. For example, one might have been asked, "Which year had the most people 'Planning on Work' in Illinois? 1981 or 1982?" Every comparison question was of the same form. The questions were designed to evaluate different horizontal virtual distances.

For insight tasks, users were asked to state three observations about any of the data presented to them in the visualization. We recorded the observations and the time to complete each observation. Each observation was coded for its degree of detail on a Likert-scale from one to seven (detailed to overviewed respectively). The following is the scale used to rate the level of detail for each user observation:

Rating	Rule: Description of Observation
1	Observation regarding one population in one state in one year
2	Observation regarding one population in one state over two or more years
3	Observation regarding one population in one state over all years
4	Observation regarding one population over two or more states over all years
5	Observation regarding one population over all states over all years
6	Observation regarding two or more populations over all states over all years
7	Observation regarding all populations over all states over all years

Table 6.2: Rules for rating the level of detail of a user's observation

6.2.4 Procedure

Each participant was asked to come to two sessions. One session took about one hour to complete. Before beginning the first session, participants were asked to fill out a demographic questionnaire as well as inform the proctor of any physical conditions such as color-blindness or claustrophobia. Participants then had a training session for each task type, understanding how to recognize the search target and interpret the demographic visualization before beginning the experiment. Participants were told to start each task by standing at a marked 'X' on the floor, which was set to 30 inches from the center of the display. They were told that they could move from their starting position once the task began.

Participants were given written instructions for each comparison task. After every task, participants were verbally asked to rate their frustration level on a Likert scale from one to seven.

6.3 Results

Quantitative results for each task type were analyzed separately because we are not concerned with the performance difference between task types. For all tasks, the dependant variables were time to completion, frustration level, and physical movement. Insight tasks also had the dependant variable degree of detail. One participant's physical movement results were thrown out due to an incomplete recording.

6.3.1 Search Tasks

For search tasks, we performed 3-way ANOVAs on form and region. For time to completion, there were no statistically significant results. However, there were interesting results worth noting. The main effect for region (F(6,64)=1.861, p=.086) and the interaction between form and region (F(6,64)=1.406, p=.211) (Figure 6.8) show interesting trends.

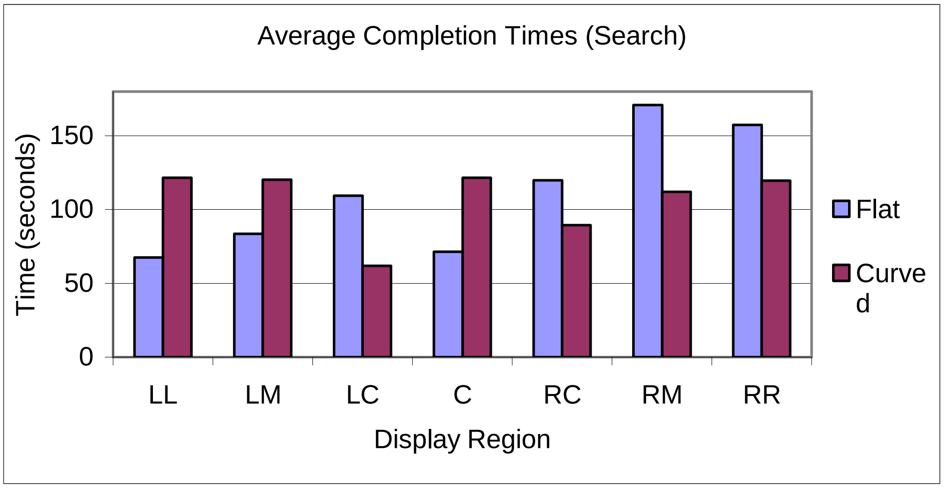

Figure 6.8: Average time to complete search tasks on each form by region

When the regions are grouped into three areas, left (LL, LM), center (LC, C, RC), and right (RM, RR), then there is an interaction between form and area (F(2,224)=3.537, p=.03) (Figure 6.9). Post-hoc one-way ANOVAs show that users search faster on the flat left area than on the flat right area (F(2,224)=6.055, p=.003).

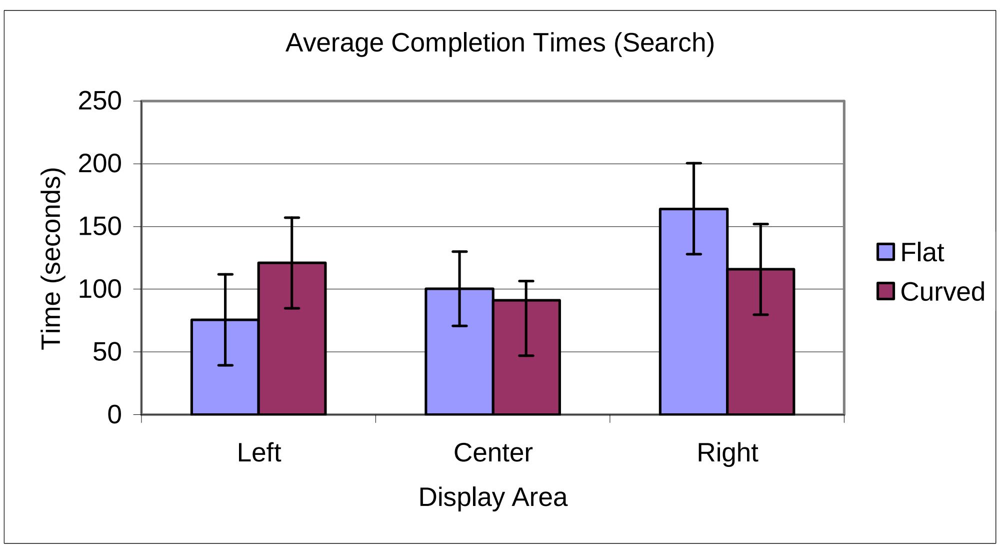

Figure 6.9: Average time to complete search tasks on each form by area

For frustration level, there was a significant main effect for form (F(1,224)=6.747, p=.01) where participants found the curved form less frustrating than the flat form (Figure 6.10).

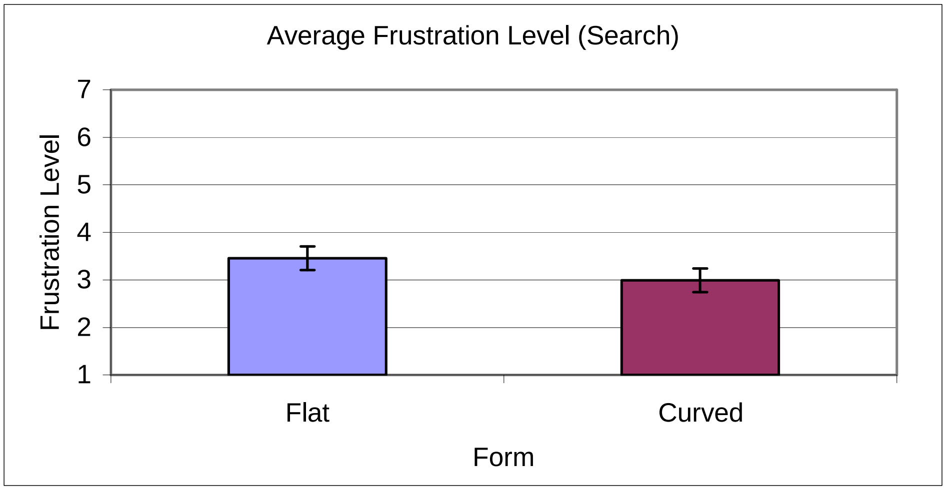

Figure 6.10: Average frustration level for the two forms

For physical movement, there was a significant main effect for form (F(1,210)=18.542, p<.001) where participants moved the position of their heads less on the curved form (Figure 6.11). There was also an interaction between form and region for moving the position of their body (F(6,210)=2.172, p=045). Post-hoc one-way ANOVAs show that participants moved the position of their body less on the curved form (F(1,210)=14.352,p<.001) (Figure 6.11).

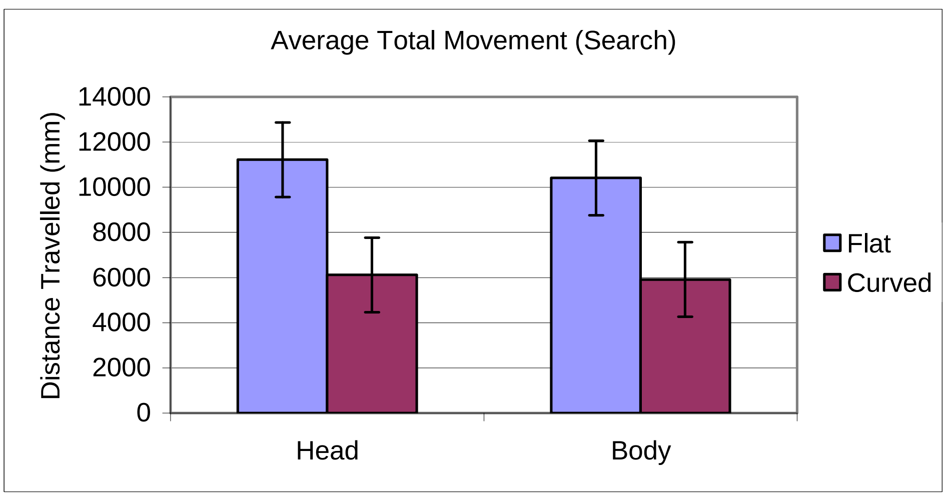

Figure 6.11: Average total head and body movement on the two forms

6.3.2 Comparison Tasks

For comparison tasks, we performed a 2-way ANOVA on form and virtual distance. For time to completion, there was a statistically significant main effect for virtual distance ($F(6,64)=7.073$, $p<.001$). This is not surprising, since the difficulty of analyzing virtually more distant objects is already understood. Although we cannot reject the null hypothesis that users do not perform differently (faster) on the curved form for comparison tasks at greater virtual distances, we believe this may be for two reasons. First, we observed some users would run across the flat display to make the same time. Second, the tasks were perhaps too simple and did not require enough cognitive load. Therefore, although not significant it is still worth noting the faster performance for curve in the eight column condition, despite the users that ran in the flat condition (Figure 6.12).

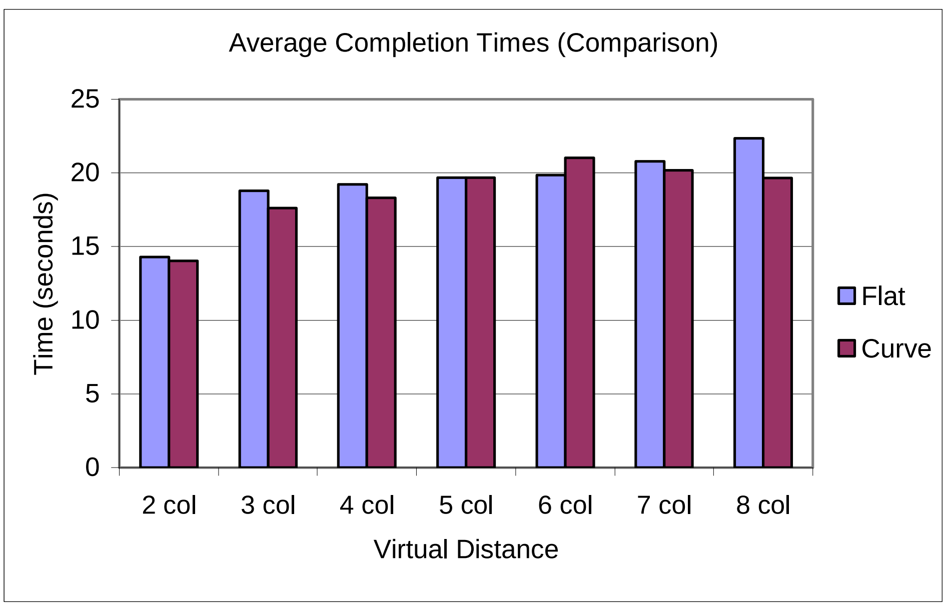

Figure 6.12: Average time to complete comparison tasks on each form by virtual distance

For frustration level, there were no statistically significant results. However, longitudinal use of large displays may prove otherwise.

For physical movement, there was an interaction between form and virtual distance for moving the position of their head ($F(6,210)=3.934, p=.001$). Post-hoc one-way ANOVAs show that participants moved the position of their head less on the curved form ($F(1,210)=35.355, p<.001$) (Figure 6.13) and participants moved the position of their head less with shorter virtual distances ($F(6,60)=4.281, p<.001$) (Figure 6.14).

There was also an interaction between form and virtual distance for moving the position of their body ($F(6,210)=4.432, p<.001$). Post-hoc one-way ANOVAs show that participants moved the position of their body less on the curved form ($F(1,210)=38.272, p<.001$) (Figure 6.13) and participants moved the position of their body less with shorter virtual distances ($F(6,60)=5.147, p<.001$) (Figure 6.14).

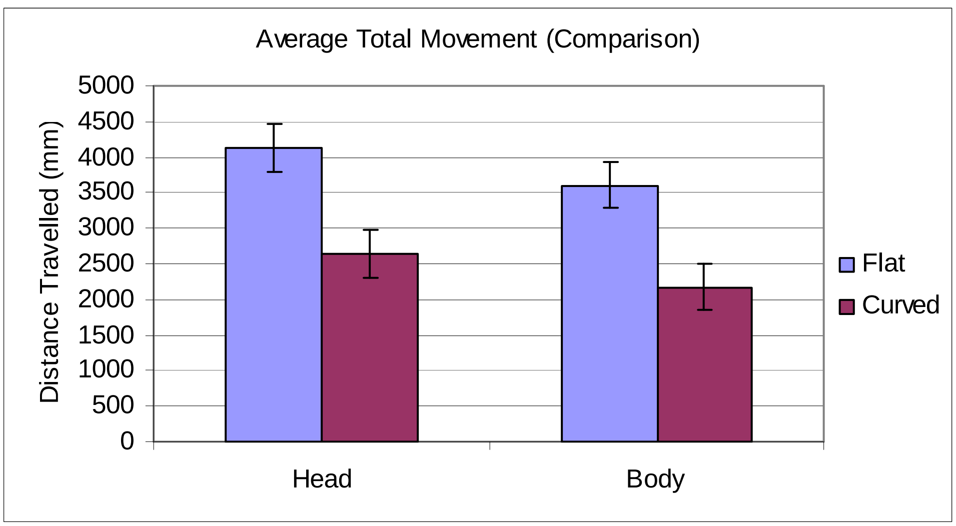

Figure 6.13: Average total head and body movement on the two forms

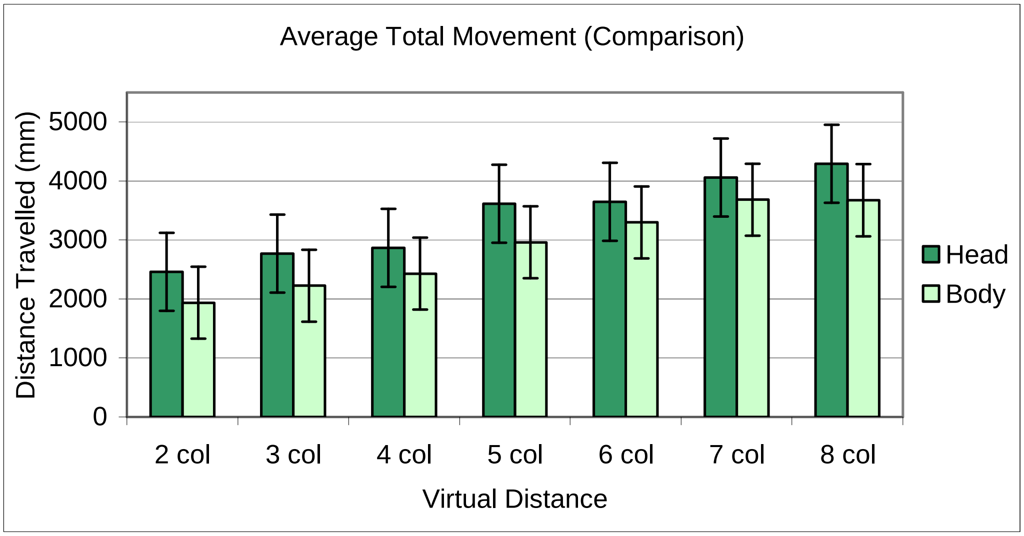

Figure 6.14: Average total head and body movement on the seven virtual distances

There was a main effect of form for turning their body ($F(1,210)=14.919, p<.001$) showing that participants turned significantly more on the curved display (Figure 6.15).

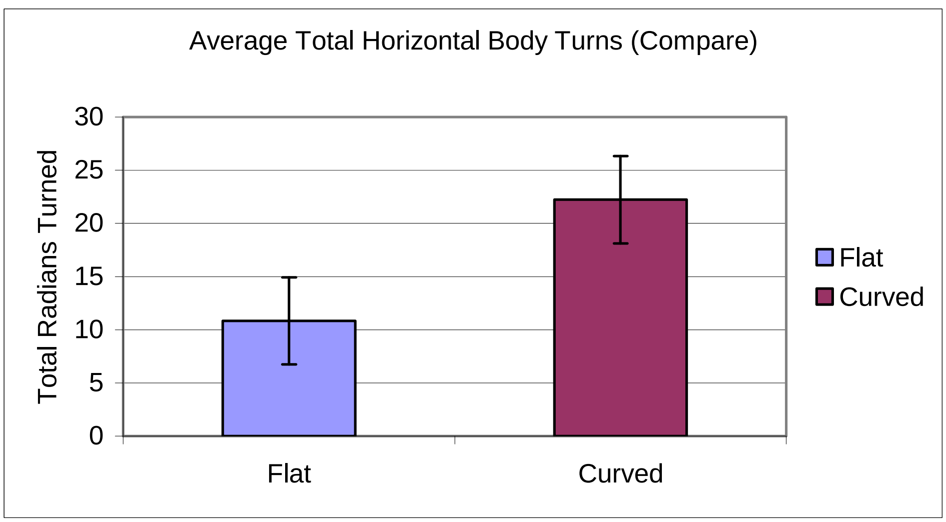

Figure 6.15: Average total horizontal body turns on the two forms

6.3.3 Insight Tasks

For insight tasks, we performed a 2-way ANOVA on form and insight order. Because we recorded the time to complete each observation, the order corresponds to the order in which the observations were made. For time to completion, there was a significant main effect for the insight order ($F(2,96)=9.511$, $p<.001$) where the first insight took the longest and the second insight was the fastest (Figure 6.16).

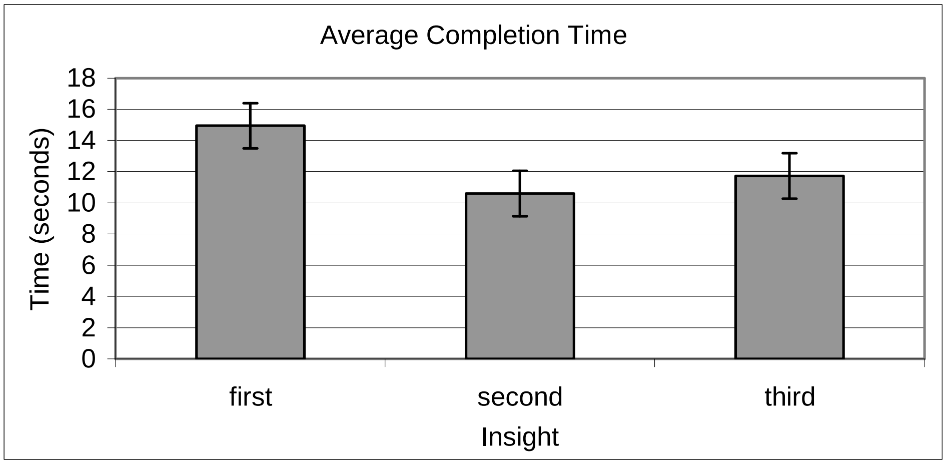

Figure 6.16: Average completion time for insight order

For insight degree of detail, there was a close to significant main effect for form ($F(1,144)=3.718$, $p<.055$) with more detailed insights on the curve form and more overview insights on the flat (Figure 6.17).

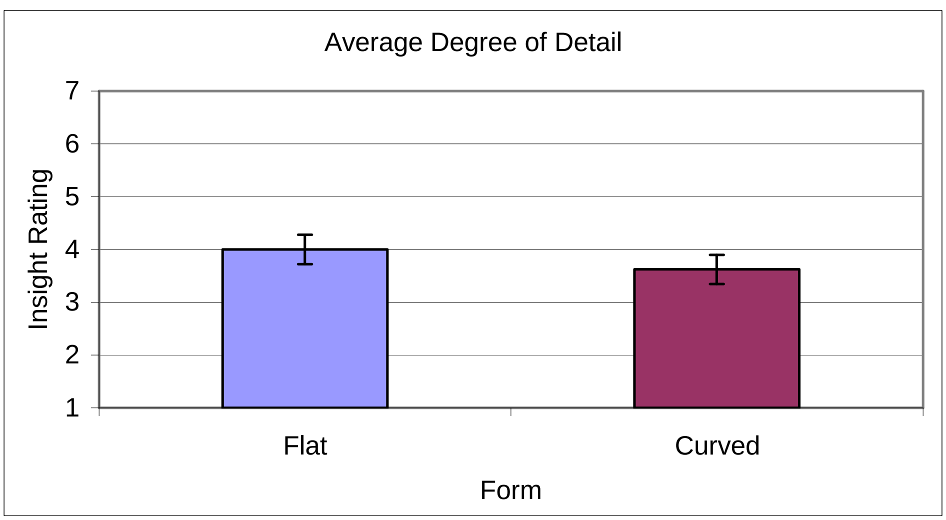

Figure 6.17: Average degree of detail on the two forms

For frustration level, there were no statistically significant results.

For physical movement, there was a statistically significant main effect for form ($F(1,130)=47.188$, $p<.001$) showing that participants moved the position of their head less on the curved form. There was also a main effect for form ($F(1,130)=33.763$, $p<.001$) where participants moved the position of their body less on the curved form (Figure 6.18).

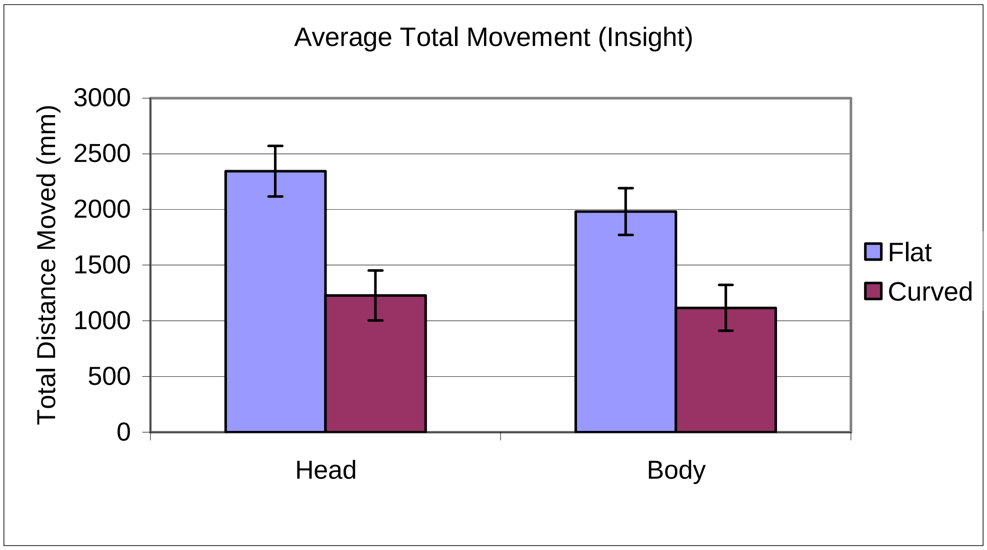

Figure 6.18: Average total head and body movement on the two forms

6.3.4 Summative Evaluation

In the post-experiment questionnaire, participants were asked to select which form he/she preferred for each task type and overall. There is a clear preference for the curve form for comparison tasks (75%), a slight preference for the curve form on search tasks (56.25%) and overall (50%). There is also a slight preference for the flat form for insight tasks (43.75%), which may be because people tend to look for overview observations and perhaps feel more accomplished having made an observation about more of the data. The following is a histogram showing the total number of participants and their preference for flat, curved, or neither (Figure 6.19).

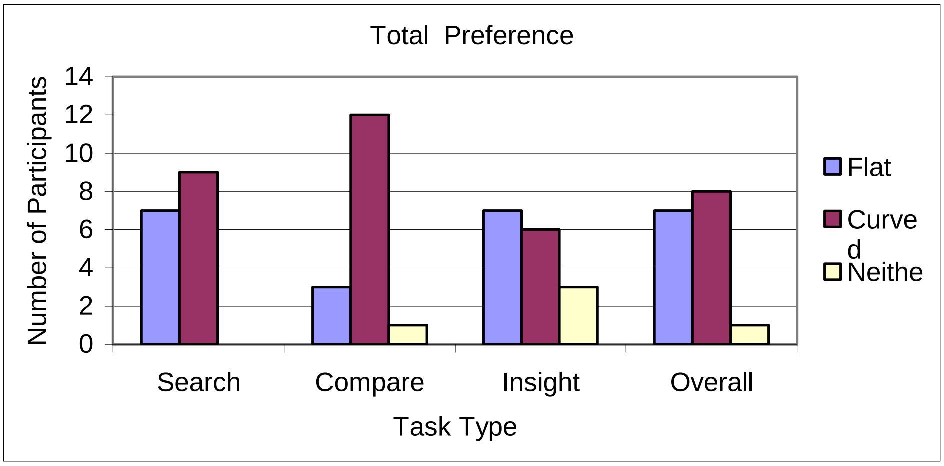

Figure 6.19: Total number of participants who preferred each form for the three task types and overall

6.3.5 Observations

While conducting our study, we annotated any interesting behaviors or patterns participants had, as well as any comments they made. Also, in the post experiment questionnaire we asked participants to elaborate on what they thought of the tasks and the display form. The following describes those observations and comments.

For the search tasks, there was a broad range of strategies employed by participants. The most common searching strategy was to scan the monitors left to right and top to bottom. When the water tower target was on the left side of the screen, participants found it faster than when it was on the right side. This is illustrated in Figure 6.9. Other strategies included scanning the monitors by row top to bottom, scanning the middle columns first then moving outwards, and quickly scanning the whole display until the water tower “popped out.” Often times, participants that usually found the water tower quickly would verbalize frustration earlier than slower participants.

On the post experiment questionnaire, nine of the participants preferred the curved form and seven preferred the flat form for the search tasks (Figure 6.19). All of the participants who preferred the curved display said they didn't have to move as much to see the screens and it made it easier to scan the screens quickly. Of the seven participants that preferred the flat display, three of them said they liked to back up and move around while searching for the water tower. One of the participants commented that the flat display seemed more "normal" to them, and two of the participants said the flat display helped them search in a grid pattern.

On the comparison tasks, many participants said they would visualize where the data would be located on the screen in their minds before beginning the task. They said this helped them make more efficient use of their time once the task began. Also, when asked to compare data that was eight columns apart on the flat display, some participants would run back and forth to see both data points. Another observation was that more participants used their arms when the display was curved as opposed to flat. We believe this is because when the display was curved you could touch all points of the screen from the middle of the display, whereas when the display was flat participants could not touch the data at the edges of the display at the same time.

On the post experiment questionnaire, twelve of the participants preferred the curved form and three preferred the flat form on the comparison tasks (Figure 6.19). All of the participants who preferred the curved form on this task said that it was because they could easily see all the points on the screen. Four of those participants elaborated further and said that they liked being able to touch the screen and see the data points without having to move. All three of the participants who preferred the flat display on this task said that it was because it felt more "normal" and it was easier to see the alignment of data points.

On the post experiment questionnaire, six of the participants said they preferred the curved form for insight tasks and seven said they preferred the flat form (Figure 6.19). The remaining five participants had no preference. Surprisingly, all of the participants had very similar responses for they preferred a certain form factor. All six of the participants who preferred the curved form said this was because it was easier for them to see trends in certain populations. All seven of the participants said they preferred the flat form because it was easier to step back and see all of the data points.

Since all of the participants experienced both form factors of the display, several of them had initial opinions of what they thought of the two display forms. One participant who had the curved form for their first set of tasks returned to finish the experiment when the display was in its flat form. He said, “Whoa, this is going to be so much harder.” When asked why he felt that way, he said that it looked like so much more to take in at once. Two participants who started on the flat form first said that they wish the display was curved around them. They said it would be easier to see details if the display was closer to them.

On the post experiment questionnaire, eight of the participants said they preferred the curved form overall and seven of the participants said they preferred the flat form. All of the participants who preferred the curved display said that it was because they could see all the data without having to move much. One participant went on to say that the curved display was more “immersive” and helped them focus on their tasks. Of the participants who preferred the flat condition, three said it was because it felt more “normal” and another three said it was because they could step back and see all the information at once.

6.4 Conclusions

For all three tasks (search, comparison, and insight) users moved the position of their heads and bodies significantly more, approximately twice, on the flat display than on the curved display. If objects were virtually farther apart, users also moved their heads and bodies significantly more to compare them. For comparison tasks, users turned their bodies significantly more on the curved form than on the flat. The reduction in physical navigation is the most likely cause of the improved user performance times on the search tasks, preference for curved on comparison tasks, and more detailed insights.

When looking for an object on our display, users favor the left side of the flat display over the right side. Alternatively, on the curved display there are no significant differences. Therefore, curving the display seems to remove any bias users have towards the left of the display. Furthermore, users are less frustrated searching on the curved display. This may be because the average time to find the object is less dependant on its location, whereas on the flat display users tend to favor the left region. There were two more users who preferred the curved display than the flat for search tasks. Why not more? Based on user comments it appears that some preference for the flat display is because of familiarity with that form and its support for searching by grids. However, with the evident performance benefits and lowered frustration levels measured from the same users, this preference for curved displays will most likely grow with more use.

When comparing two objects, user performance time significantly depends on the virtual distance. As the virtual distance between objects increases, the performance time also increases. Although, there is no statistically significant difference in performance time between the flat and curved conditions, we believe this is primarily because some users would compensate for the extra physical navigation needed on the flat display by running. Therefore, it appears that normal, long-term use of the display would in actuality result in slower performance times on the flat display when comparing objects at greater virtual distances. Although it may not be certain whether there are significant performance benefits for comparison tasks on a curved display at this size, it is clear that users strongly prefer this form for comparison tasks. With seventy-five percent of users preferring the curved form over the flat, the curved form indeed appears to be beneficial for this type of task. Nevertheless, at the least the virtual distance between objects should be taken into consideration when designing interfaces for single users working on a large display with multiple views or windows, especially if the display is flat.

Furthermore, there appears to be a tradeoff of insight degree of detail on the two forms. On a flat display as large as this one, a user's first insights will be more overviewed. This means users will make large-scale observations about the data (e.g. trends). This may be because users can step back and visually aggregate all the data at a single moment when the display is flat. Whereas, the first insights a user will make on this curved display will be more detailed, such as making observations about sub-groups of the data (e.g. anomalies). This may be because users can not see all of the data points at the same moment. Users seem to prefer the flat display over the curved by a slight majority. This may be because users perceive more overviewed insights as more valuable, and their instinct was to find (more meaningful) high-level observations. Thus, they prefer a display that better equips them to make such insights. However, an insight's degree of detail does not dictate the importance of that observation. Depending on the data, either a single data point or a trend in the data may be critical. Therefore, the tradeoff found is not an advantage of one form over another, but rather a distinction.

Chapter 7

Conclusions

7.1 Summary

In both experiments, we evaluated the curvature of a large, high-resolution (96 DPI), high-pixel-count (up to approximately 32 million pixels) display for basic, yet realistic, geospatial tasks. The first experiment reveals performance benefits for our standard flat twenty-four monitor display as well as when the display is curved. The second experiment further evaluates curvature, uncovering some of the weaknesses of the flat display, as well as a tradeoff in insights.

The first experiment began by determining that a display of this size is indeed beneficial. To do so, three viewport conditions were evaluated: one, twelve, and twenty-four monitor displays. The results, summarized in Table 7.1, show that increasing the viewport size (increasing pixel-count while maintaining pixel density) improves user performance. Over all three tasks (search, route tracing, and image comparison), the larger display sizes improved performance over smaller sizes. On search tasks specifically, both the twelve and twenty-four monitor conditions improve performance over one monitor, and subjects performed 2-6 times faster. For route tasks, the twenty-four monitor condition improves performance over the twelve monitor condition and subjects performed approximately 50% faster. Thus, it appears that as one increases the display size, adding more pixels, users can improve their performance times, depending on the task. Furthermore, observations show a reduction in virtual navigation and increase in physical navigation. Therefore, the combination of increasing visual imagery and physical navigation is beneficial. We also found that user frustration is significantly less on the larger displays than on the one monitor condition. This might correspond to the greater use of human visual capacity and more natural physical navigation that reduces potential frustrations of virtual navigation.

Effect	1 mon	12 mon	24 mon
Faster performance time for search		✓	
Faster performance time for route tracing			✓
More virtual navigation	✓		
More physical navigation		✓	✓
Less user frustration		✓	✓

Table 7.1: List of effects for each viewport size

At the same time, the first experiment evaluated two conditions where the large displays (twelve and twenty-four) were curved. Findings show that curved displays improve performance over flat displays regardless of viewport size. For easy tasks, curvature performance was approximately 30% faster than flat. Of all five display conditions, user performance was the best on the curved twenty-four monitor condition. Curvature improved performance probably because users could better utilize the left and right outermost pixels on the display (as shown in section 5.1). In the flat twenty-four monitor condition, for example, users were at least 4 feet away from the furthest pixels. However, in the curved twenty-four monitor condition the user was never more than 2.5 feet from any given pixel. Observations show that physical navigation changes from standing and walking on the flat display to turning when the display is curved. The change in physical navigation supports our visual acuity hypothesis. The fact that curved displays improve performance indicates that this type of physical navigation was more efficient for users and better enabled them to visually access and process the imagery.

The second experiment further evaluated the curvature of displays to understand why users benefit from them. Specifically, the experiment sought to measure the amount of physical navigation while evaluating whether users have a bias towards certain regions of the display, whether the virtual distance is a factor, and whether the degree of detail changes on the two forms. For all three tasks (search, comparison, and insight) users moved the position of their heads and bodies approximately twice as much using the flat display than when using the curved display. This means that the change in physical navigation observed in the first experiment is significantly less movement as well. The second experiment also shows that if objects are virtually farther apart, users moved their heads and bodies significantly more to compare them. The reduction in physical navigation and improved visual access to all the pixels are most likely the cause of improved user performance times on search tasks, preference for the curved form on comparison tasks, and more detailed insights.

Search tasks were used to evaluate any biases towards regions of the display. Results show that users favor the left side of the flat display over the right side. Alternatively, on the curved display there are no significant differences. Therefore, curving the display seems to remove the bias users have towards the left of the display. Furthermore, users are less frustrated searching on the curved display. This may be because the average time to find the object is less dependant on its location, whereas, on the flat display users tend to favor the left region. Therefore, not only are larger displays less frustrating, but one could argue that curved large displays are the least frustrating.

Comparison tasks were designed to evaluate whether the form of the display improved performance gaps at greater virtual distances. The results show that indeed user performance time significantly depends on the virtual distance. As the virtual distance between objects increases, the performance time also increases. Although, there is no statistically significant difference in performance time between the flat and curved conditions, we believe this is primarily because some users would compensate for the extra physical navigation needed on the flat display by running. Therefore, it appears that normal, long-term use of the display would in actuality result in slower performance times when comparing virtually distant objects if it were flat than curved. As a result, the virtual distance between objects should be taken into consideration when designing interfaces for single users working on a large display with multiple views or windows, especially if the display is flat.

The insight tasks were designed to see whether there is a tradeoff in an insight's degree of detail on the two forms. The results show that there is a tradeoff (94.5% confidence). On a flat display as large as this one, a user's first insights will be more overviewed. This means that users will make more large-scale observations about the data (e.g. trends). Whereas, the first insights a user will make on this curved display will be more detailed, such as making observations about sub-groups of the data (e.g. anomalies). Users seem to prefer the flat display over the curved with a slight majority. This may be because users perceive overviewed insights as more valuable, and their instinct is to find (more meaningful) high-level observations. Thus, they prefer a display that better equips them to make such insights. Furthermore, users take more time making the first insight than the second and third.

The results show that as you increase the pixel-count (up to approximately 32 million pixels) of a high-resolution (96 DPI) display that users will perform faster, depending on the task, with more physical navigation and less frustration, and that users improve performance time on tasks when the display is curved, bringing all the pixels into visual range, with a change in physical navigation [31]. Further evaluation shows that users have region biases on the largest display when flat, there is a trend towards greater performance loss on the flat display as virtual distances increase, and there is a tradeoff in degree of detail of a user's insight on the two forms.

The tradeoff of an insight's degree of detail on the two forms highlights the importance of reconfigurable displays. Because any insight may be of critical importance no matter how detailed the observation, it is important to improve accessibility to the data. Therefore, a quickly reconfigurable display could allow a user to switch from a form where they are apt to make overviewed insights (flat display) to a form where they can better observe details (curved display).

Based on the viewport findings, it is clear that our twenty-four monitor display is not too big. Therefore, there is still room to grow in pixel-count and potentially improve performance further. The results, summarized in Table 7.2, reveal many advantages of curving for two-dimensional, geospatial tasks.

Effect	Curved	Flat
Faster performance time (30%)	✓	
More turning	✓	
More walking		✓
Less physical navigation (50%)	✓	
Users change area of focus frequently	✓	
No region biases	✓	
More detailed initial insights	✓	
More overviewed initial insights		✓
Less user frustration for search	✓	
User preference for search	✓	
User preference for comparison	✓	
User preference for insight		✓

Table 7.2: List of effects for each form

In general, individuals who work on similar tasks should curve his/her large, high-resolution display. If space is an issue, start curving once the display reaches about four or five monitors wide. It is clear that the change and reduction in physical navigation by curving improves the user experience, significantly impacting the work of professionals such as image analysts.

Furthermore, the ability to easily reconfigure opens doors to different insights. Not only will the workforce be more efficient using a curved, large, high-resolution display, but they may prefer the less strenuous, less frustrating experience.

7.2 Towards a Curvature Model

The empirical results of this work suggest a model for interaction with large displays. Increasing the viewport size and curving the display influences the user's experience. Understanding why viewport size and curvature affect performance and insights will help build a model for greater viewport sizes and varying curvatures.

The addition of pixels both increases the details shown in the peripheral imagery and makes use of natural physical navigation, improving performance. The visual gain and physical input are potentially building a greater sense of embodiment. The additional peripheral imagery better enables users to build mental models of the spatial data with which they are working. The natural physical navigation affords better recall and recognition of spatial properties based on muscle memory. However, the performance gain may drop off as the outermost pixels become increasingly more difficult to access by translational physical navigation (i.e. walking). Therefore, at some point adding more pixels to a flat display no longer improves performance.

Alternatively, curving the display around the user affords more efficient natural movements (i.e. turning), allowing users to utilize more of the display in the same amount of time. The ability to change area of focus quickly better equips users to find, trace, and compare objects. Therefore, the greater the viewport size, the more curving the display improves user performance for such tasks. Because all the details are more accessible and encourage more efficient natural movements, users also no longer consciously pick a region of the display as a starting point (no region bias). Furthermore, because the display surrounds the user, it creates a sense of immersion. This may be the reason behind the more detailed insights. If the user is already immersed in the display, he/she will begin making observations at the current area of focus, missing values at other locations on the screen. Although it is possible to walk backwards, the tight curvature does not invite the user to step back and observe the entire data set as much as when the display is flat.

How does the effect of curvature scale with greater viewport sizes? Consider the curve evaluated in this work. The radius of the curve was held constant. As the width of the display increases, eventually the display would form a circle. To increase the viewport size further, the radius would also have to increase. Therefore, to develop a model for performance or insights it is clear that the radius of the curve is an important factor. Let us assume that the radius of the display would increase proportionally with the viewport, maintaining a half circle. Eventually the viewport size of a flat display will be so large that the user can not make use of the entire display. Performance benefits will reach a limit. As the viewport size becomes infinitely large, a curved display will essentially be a flat display. In effect the performance benefits of a curved display will also reach a limit, perhaps eventually reducing to that of a flat display. In theory, performance benefits could be modeled as seen in Figure 7.1.

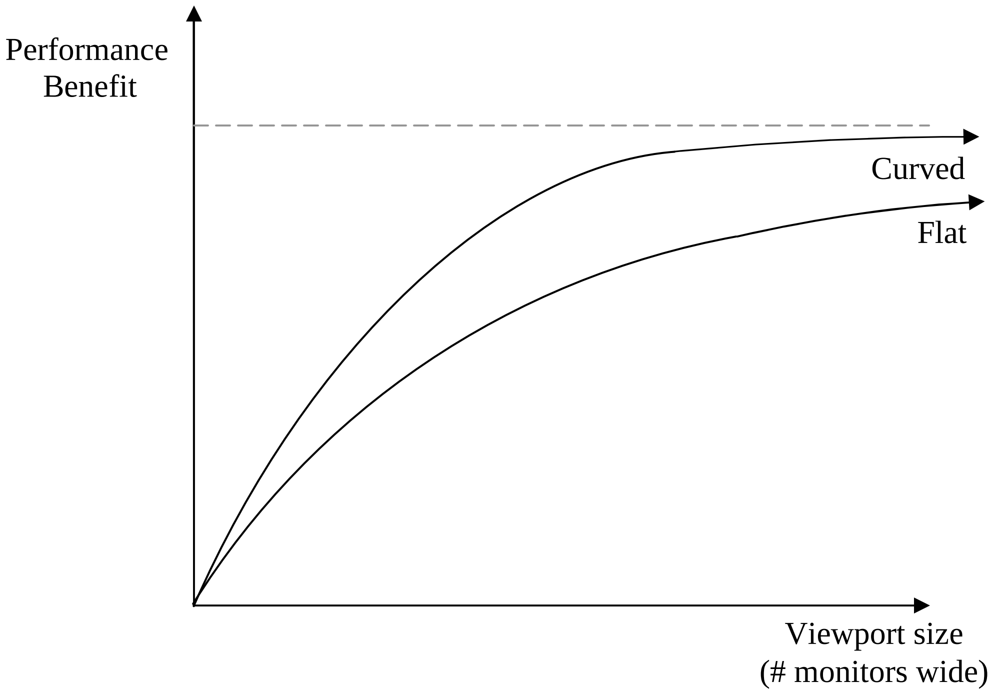

Figure 7.1: Model for performance benefit of both flat and curved displays with respect to viewport size

The tradeoff of user insights may be modeled similarly. The difference between an insight's degree of detail on the flat and curved display may increase as the viewport size increases. Consider a viewport size five or ten times that of the twenty-four monitor display evaluated here. Assume the density of the data remains constant. In other words, as the viewport size increases the extent increases. Because there is more data on a larger viewport size available to the user, there is potential to make more overviewed insights. When observing on a flat display, users are more likely to step back farther, putting more pixels outside the visual acuity range. The user visually aggregates the data, in turn achieving the more overviewed observations. However, as the viewport size becomes infinitely large, the user can not utilize the entire display. Thus, the degree of detail reaches a limit. Conversely, if the display is curved, users will continue to make observations within their focus area. Because the focus area flattens as the radius of the curve increases, the gap in degree of detail will close. In theory, the degree of detail for insights could be modeled as seen in Figure 7.2.

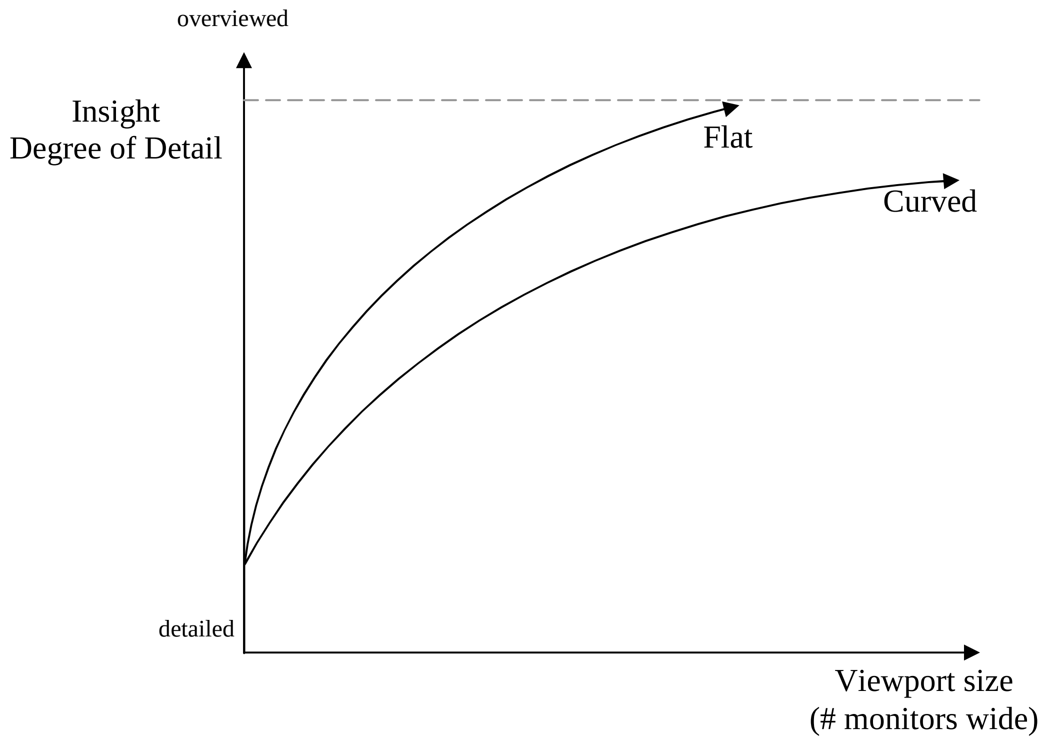

Figure 7.2: Model for insight degree of detail for both flat and curved displays with respect to viewport size

7.3 Future Work

All tasks evaluated in this work involve two-dimensional geospatial imagery or visualizations. None of the tasks required users to understand the geometric relationships between distant objects. Future work is necessary to understand whether there are any disadvantages curving may have on a user's perception of the distorted imagery. Or can users do the mental transformations necessary to think of the imagery as flat?

Furthermore, can users correctly perceive three-dimensional data when the display is curved? With no adjustments made to the scene rendered, the view will be distorted. However, making adjustments to the scene to accommodate distortion would be increasing the field of view, but fewer pixels in the periphery would be used to represent objects in the scene. This would go against the visual advantage of having the outside pixels closer.

Once we understand the effects of curving on both two and three-dimensional data in the one space paradigm, it would be very useful to understand how much curvature affects the partitioned space paradigm. Because users tend to work with multiple windows, switching their attention often, it would be beneficial to understand how curvature might help with common tasks. Based on the comparison tasks of the second experiment, this may be a strength for curved displays. Because the greater virtual distances affect performance negatively, a study using the partitioned space paradigm (using different spaces on the display as different rooms) should provide guidance for interface designs. In particular, likely design improvements are for desktop organization, window placement, and interaction techniques.

Evaluating the partitioned space paradigm would be difficult to study without an input device. Therefore, it is important to find appropriate input devices for large displays, as well as understanding if the curvature of the display influences which input devices is ideal. For example, tiled touch screen monitors may be sufficient for curved displays, but a weakness when the display is flat. Conversely a six degrees of freedom hand-held mouse may be best suited for a flat display, but less accurate when a user is close to a curved display.

Lastly, as displays continue to grow in pixel-count and size, while maintaining a high-resolution, curvature may continue to be a significant factor in the user experience. Therefore, further evaluations of curvature are necessary for displays with greater pixel-count and greater resolution than this twenty-four monitor display. In particular, evaluating different curves would be helpful. Therefore, it is also important to discover how the radius of the curve on increasingly larger viewport sizes affects the user experience.

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Appendix A: Experiment 1

A.1 Participant Instructions

Thank you for participating in this experiment.

You will be asked to perform a set of tasks using a map viewing program. These tasks consist of navigating through satellite images at different scales. We are not evaluating you; rather, you are helping us to evaluate the interface. All information that you help us attain will remain anonymous. The time you take to do each task and other aspects of your interaction with the display will be measured. You may be asked questions during and after the evaluation.

The session will last about one hour. Each task will be no longer than 5 minutes. You are welcome to take rest breaks as needed. One scheduled rest break will be given about half-way through the experiment. You may also terminate your participation at any time, for any reason.

You will have the opportunity to explore the program before beginning the experiment. Before each task, you will be given full instructions. It is important that you understand the instructions before beginning each task. If anything is unclear, be sure to ask before beginning the task. Also, do not feel restricted to your seat. Feel free to get up and move around when necessary.

The results of this study will be kept strictly confidential. The information you provide will have only a number to identify your evaluation. If you know of any conditions that may affect your participation in this task such as prior knowledge of the geographic areas used, prior experience with GIS, or any medical condition such as colorblindness, please inform the proctor.

A.2 Demographic Questionnaire

Please help us to categorize our user population by completing the following questions.

Gender (circle one): Male Female

Age: _____________

Do you wear glasses or contact lenses (circle one)? No Glasses Contact Lenses

Occupation (if student, indicate graduate or undergraduate):__________________________

Major / Area of specialization (if student): _________________________________

How often do you use computers? _______________________________________

Have you ever used a large display? If so, please describe it (what type of display was used, what kind of application was running, how did you interact with the system, etc.).
____
____

I am familiar with computers: (circle one)

1 Strong Disagree
2 Somewhat Disagree
3 Undecided
4 Somewhat Agree
5 Strongly Agree

I am familiar with large displays: (circle one)

1 Strong Disagree
2 Somewhat Disagree
3 Undecided
4 Somewhat Agree
5 Strongly Agree

I am familiar with the field of Information Visualization: (circle one)

1 Strong Disagree
2 Somewhat Disagree
3 Undecided
4 Somewhat Agree
5 Strongly Agree

I am familiar with geographic information systems: (circle one)

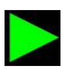
1 Strong Disagree
2 Somewhat Disagree
3 Undecided
4 Somewhat Agree
5 Strongly Agree

For Researcher Use Only
Subject Number: ________________
Visualization Design: _____________

A.3 Task Questions

In this satellite view, find as quickly as you can the building with a red bullseye  on its roof.

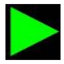
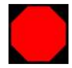
The airport on the screen has many runways. A runway is a special straight road that airplanes use to take off and land. If you have any questions about what a runway is, please ask now. Every runway has labels painted on both ends. Every label at the end of a runway has a number and letter. Find the runway end that is labeled, "14 R".

Note the green arrow  and red octagon  icons on the screen. Your task is to trace Highway 63 starting at the green arrow and ending at the red octagon. As quickly and accurately as possible, "check" all the **overpasses** where highway 63 goes **over** another road.

You may left click on the road to "check" that there is an overpass. Right clicking removes the check.

Tell the proctor when you have found the last overpass.

Example of a highway 63 overpass

Note the green arrow  and red octagon  icons on the screen. Trace highway 8 starting at the green arrow and ending at the red octagon. As quickly and accurately as possible, "check" the **underpasses** where highway 8 goes **under** another road.

You may left click on the road to "check" that there is an underpass. Right clicking removes the check.

Tell the proctor when you have found the last underpass.

Example of a highway 8 underpass

In this scenario you will be able to toggle between two satellite views using the **"u" key**. One is an older black and white view and the other is a newer view in color.

Your task is to identify blocks where there have been **urban changes**. For example, an urban change is where there are new buildings, destruction of old buildings, and new roads. **This does not include trees, water or other earthworks.** There is a grid on the screen to identify the blocks you want to look at.

You may left click on a block to "check" that there is a change. Right clicking removes the check.

If there is a change that crosses over more than one block, check all blocks that it overlaps.

As fast as you can, check as many blocks on the grid that have urban changes. You will have 5 minutes.

A.4 Statistical Analysis

Completion Times

The following corresponds to the 3-way ANOVA for time to completion.

General Linear Model: performance versus monitor, type, easy/hard

Factor	Type	Levels	Values
monitor	fixed	5	1 mon, 12 curved, 12 mon, 24 curved, 24 mon
type	fixed	2	route, search
easy/hard	fixed	2	easy, hard

Analysis of Variance for performance, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
monitor	4	89896	89896	22474	3.53	0.009
type	1	858553	859713	859713	134.90	0.000
easy/hard	1	95560	98078	98078	15.39	0.000
monitor*type	4	67887	67887	16972	2.66	0.035
monitor*easy/hard	4	9813	9813	2453	0.38	0.819
type*easy/hard	1	3314	2689	2689	0.42	0.517
monitor*type*easy/hard	4	26420	26420	6605	1.04	0.391
Error	136	866705	866705	6373		
Total	155	2018148				

S = 79.8300   R-Sq = 57.05%   R-Sq(adj) = 51.05%

The following corresponds to the 3-way ANOVA for time to completion on curvature and viewport size for easy tasks.

General Linear Model: performance versus type, viewport size, curved/flat

Factor	Type	Levels	Values
type	fixed	2	route, search
viewport size	fixed	2	12, 24
curved/flat	fixed	2	curved, flat

Analysis of Variance for performance, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
type	1	466498	458351	458351	181.19	0.000
viewport size	1	16911	18655	18655	7.37	0.009
curved/flat	1	19755	20300	20300	8.02	0.006
viewport size*curved/flat	1	3390	3390	3390	1.34	0.252
type*viewport size	1	25410	25261	25261	9.99	0.003
type*curved/flat	1	1785	1643	1643	0.65	0.424
type*viewport size*curved/flat	1	2414	2414	2414	0.95	0.333
Error	54	136605	136605	2530		
Total	61	672769				

S = 50.2964   R-Sq = 79.70%   R-Sq(adj) = 77.06%

The following corresponds to the 1-way ANOVA for time to completion on easy search tasks.

General Linear Model: performance versus monitor

```
Factor   Type   Levels  Values
monitor  fixed       5  1 mon, 12 curved, 12 mon, 24 curved, 24 mon


Analysis of Variance for performance, using Adjusted SS for Tests

Source   DF  Seq SS  Adj SS  Adj MS     F      P
monitor   4   55576   55576   13894  4.03  0.009
Error    34  117342  117342    3451
Total    38  172918


S = 58.7473   R-Sq = 32.14%   R-Sq(adj) = 24.16%
```

The following corresponds to the 1-way ANOVA for time to completion on easy route tasks.

General Linear Model: performance versus monitor

```
Factor   Type   Levels  Values
monitor  fixed       5  1 mon, 12 curved, 12 mon, 24 curved, 24 mon


Analysis of Variance for performance, using Adjusted SS for Tests

Source   DF  Seq SS  Adj SS  Adj MS     F      P
monitor   4   58886   58886   14722  3.84  0.011
Error    34  130326  130326    3833
Total    38  189212


S = 61.9121   R-Sq = 31.12%   R-Sq(adj) = 23.02%
```

Appendix B: Experiment 2

B.1 Informed Consent for Participant of Investigative Project

I. THE PURPOSE OF THIS RESEARCH/PROJECT

You are invited to participate in a study of visualizations on large high-resolution displays. This study involves experimentation for the purpose of evaluating and improving visualization techniques.

II. PROCEDURES

You will be asked to perform a set of tasks using a given visualization. The amount of information being displayed in this visualization will vary. The visualization will be displayed on a large high resolution display. The experiment may be videotaped. All information that you help us attain will remain confidential.

You may also be asked to fill out a demographic questionnaire that includes questions relating to your background with large displays and visualizations. The demographic survey will also ask for an approximation of your height. We ask this so that we may raise or lower the display to an optimal height before you begin the tasks.

Each session will last about ninety (90) minutes. The interaction is not very tiring, but you are welcome to take rest breaks as needed. You may also terminate your participation at any time, for any reason. You will be given full instructions before we start. It is important that you understand the instructions before beginning. If anything is unclear, be sure to ask us questions.

You are asked to participate in two sessions with the large screen display. One session will involve interacting with the display while it is flat, and the second session will involve interacting with the display while it is curved. Once you have completed the first session, we will then ask you to schedule when you will be able to attend the second session. If you are unsure about your schedule at this point in time, you are welcome to contact us later with possible times.

III. RISKS

Participation involves sitting or standing and interacting with a large display. The physical components of these tasks are not stressful, and include head and body movements and pointing. The only foreseeable physical risk is mild neck strain. If you experience any neck strain or any other form of discomfort please step away from the display and take a rest break. If you become uncomfortable, you will be allowed to leave with no penalty.

IV. BENEFITS OF THIS PROJECT

Your participation in this project will provide information that may be used to improve the design of information visualization for large high resolution displays. No guarantee of benefits has been made to encourage you to participate by the researchers, although individual professors may provide extra credit. You may receive a synopsis summarizing this research when completed. Please leave a self-addressed envelope with the experimenter and a copy of the results will be sent to you.

You are requested to refrain from discussing the evaluation with other people who might be in the candidate pool from which other participants might be drawn until June 30, 2006.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The results of this study will be kept strictly confidential. Your written consent is required for the researchers to release any data identified with you as an individual to anyone other than personnel working on the project. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

The experiment will be videotaped. The tapes will be stored securely, viewed only by the experimenters Lauren Shupp, Margaret Kurdziolek, and Chris North, and erased no later than July 31, 2006. If the experimenters wish to use a portion of your videotape for any other purpose, they will get your written permission before using it. Your signature on this form does not give them permission to show your videotape to anyone else.

VI. COMPENSATION

Your participation is voluntary and paid. Full participation in the experiment consists of two 90 minute sessions. After participation in the second session you will receive $5. If you perform the fastest on any of the three task types out of all the participants, you will receive a $40 prize.

VII. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time for any reason.

VIII. APPROVAL OF RESEARCH

This research has been approved, as required, by the Institutional Review Board for projects involving human subjects at Virginia Polytechnic Institute and State University, and by the Department of Computer Science.

IX. SUBJECT'S RESPONSIBILITIES AND PERMISSION

I voluntarily agree to participate in this study, and I know of no reason I cannot participate. I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project. If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project

____ ________
Signature Date

____ ________________________
Name (please print) Contact: phone or address or

____
email address (OPTIONAL)

Should I have any questions about this research or its conduct, I may contact:

Investigators:

Lauren Shupp
Graduate Student, Computer Science Department
Email: lshupp@vt.edu

Margaret Kurdziolek
Graduate Student, Computer Science Department
Email: mkurdziolek@vt.edu

Dr. Chris North Phone (540) 231-2458
Faculty, Computer Science Department
Email: north@vt.edu

Review Board:

David M. Moore
Office of Research Compliance
1880 Pratt Drive, Suite 2006 (0497)
Blacksburg, VA 24601

B.2 Demographic Questionnaire

Please help us to categorize our user population by completing the following questions.

What is your gender?

- Male
- Female

What is your age?

Age: ____

If you are older than 32, please notify the proctor.

Do you have corrected vision? Select one.

- No
- Contact Lenses
- Glasses
- other: ____

What is your occupation?

- Undergraduate Student
- Graduate Student
- other: ____

If a student, what is your area of study?

____

How often do you use computers?

- Hourly
- Daily
- A few times a week
- Once a week
- Less than once a week
- Rarely

Have you ever used a large display? This includes: any number of tiled monitors, the CAVE, etc.

- Yes
- No

If yes, what displays have you used?

Do you have claustraphobia?

- Yes
- No
- other:

If you answered yes, please notify the proctor.

Submit

B.3 Task Instructions

Search Tasks (total of 14)

Find as quickly as you can the grey tower (icon below). When you find it, point to it and say out loud that you have found it.

Observation Tasks (total of 3)

Say out loud the first **three** observations you make. An observation is anything *meaningful* you notice in the data.

Comparison Tasks (total of 14)

You will be given an individual piece of paper with the question. You will be asked to compare a **population** for a given **location** at **two different years**. Please say out loud your answer (year).

B.4 Post Experiment Questionnaire

For Search Tasks, which form do you prefer?

☐ Curved display ☐ Flat display ☐ Neither

Why?

For Comparison Tasks, which form do you prefer?

☐ Curved display ☐ Flat display ☐ Neither

Why?

For Insight Tasks, which form do you prefer?

☐ Curved display ☐ Flat display ☐ Neither

Why?

Overall, which form do you prefer?

☐ Curved display ☐ Flat display ☐ Neither

Why?

Submit

B.5 Statistical Analysis

Search Task Statistics

The following corresponds to the 2-way ANOVA for time to completion on search tasks.

Tests of Between-Subjects Effects

Dependent Variable: Time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	382049.456[a]	5	76409.891	3.507	.004
Intercept	5120091.870	1	5120091.870	234.979	.000
RegionArea	214471.506	2	107235.753	4.921	.008
Form	8443.571	1	8443.571	.388	.534
RegionArea * Form	154157.629	2	77078.815	3.537	.030
Error	9630989.464	442	21789.569		
Total	15042104.000	448			
Corrected Total	10013038.920	447			

a. R Squared = .038 (Adjusted R Squared = .027)

3. RegionArea * Form

Dependent Variable: Time

RegionArea	Form	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
C	Curved	76.667	15.066	47.057	106.276
	Flat	100.240	15.066	70.630	129.849
L	Curved	120.906	18.452	84.642	157.170
	Flat	75.484	18.452	39.221	111.748
R	Curved	115.766	18.452	79.502	152.029
	Flat	164.141	18.452	127.877	200.404

The following corresponds to the post-hoc 1-way ANOVA of time to completion for search tasks.

Tests of Between-Subjects Effects

Dependent Variable: Time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	272533.501[a]	2	136266.751	6.055	.003
Intercept	2772190.440	1	2772190.440	123.179	.000
RegionArea	272533.501	2	136266.751	6.055	.003
Error	4973693.208	221	22505.399		
Total	8027261.000	224			
Corrected Total	5246226.710	223			

a. R Squared = .052 (Adjusted R Squared = .043)

The following corresponds to the 1-way ANOVA of physical movement of the head on search tasks.

Tests of Between-Subjects Effects

Dependent Variable: HatMoved

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2728056309[a]	1	2728056309.3	18.261	.000
Intercept	31475335551	1	31475335551	210.686	.000
Form	2728056309	1	2728056309.3	18.261	.000
Error	62297549847	417	149394603.95		
Total	96545367892	419			
Corrected Total	65025606156	418			

a. R Squared = .042 (Adjusted R Squared = .040)

Form

Dependent Variable: HatMoved

Form	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C	6115.563	845.462	4453.664	7777.462
F	11218.861	843.447	9560.923	12876.798

The following corresponds to the 1-way ANOVA of physical movement of the body on search tasks.

Tests of Between-Subjects Effects

Dependent Variable: TorsoMoved

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2120628422[a]	1	2120628421.5	14.352	.000
Intercept	27928493118	1	27928493118	189.017	.000
Form	2120628422	1	2120628421.5	14.352	.000
Error	61614536182	417	147756681.49		
Total	91700563413	419			
Corrected Total	63735164603	418			

a. R Squared = .033 (Adjusted R Squared = .031)

Form

Dependent Variable: TorsoMoved

Form	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C	5914.572	840.815	4261.808	7567.336
F	10413.992	838.811	8765.167	12062.816

Compare Task Statistics

The following corresponds to the 2-way ANOVA for time to completion on compare tasks.

Tests of Between-Subjects Effects

Dependent Variable: Time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2283.886[a]	13	175.684	3.542	.000
Intercept	161082.645	1	161082.645	3247.925	.000
Form	44.377	1	44.377	.895	.345
VirtualDistance	2104.589	6	350.765	7.073	.000
Form * VirtualDistance	134.920	6	22.487	.453	.843
Error	21524.469	434	49.596		
Total	184891.000	448			
Corrected Total	23808.355	447			

a. R Squared = .096 (Adjusted R Squared = .069)

Descriptive Statistics

Dependent Variable: Time

Form	VirtualDistance	Mean	Std. Deviation	N
Curved	2 col	14.03	5.397	32
	3 col	17.63	8.115	32
	4 col	18.31	6.860	32
	5 col	19.69	7.710	32
	6 col	21.03	8.600	32
	7 col	20.19	6.990	32
	8 col	19.66	7.294	32
	Total	18.65	7.561	224
Flat	2 col	14.28	5.974	32
	3 col	18.78	6.354	32
	4 col	19.22	7.517	32
	5 col	19.69	6.161	32
	6 col	19.84	6.521	32
	7 col	20.78	7.439	32
	8 col	22.34	6.959	32
	Total	19.28	7.029	224
Total	2 col	14.16	5.649	64
	3 col	18.20	7.253	64
	4 col	18.77	7.153	64
	5 col	19.69	6.923	64
	6 col	20.44	7.595	64
	7 col	20.48	7.167	64
	8 col	21.00	7.200	64
	Total	18.96	7.298	448

The following corresponds to the 1-way ANOVA of physical movement of the head on compare tasks.

Tests of Between-Subjects Effects

Dependent Variable: HatMoved

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	232276774.6[a]	1	232276774.59	35.355	.000
Intercept	4815352778	1	4815352778.1	732.953	.000
Form	232276774.6	1	232276774.59	35.355	.000
Error	2746176850	418	6569801.077		
Total	7793806403	420			
Corrected Total	2978453625	419			

a. R Squared = .078 (Adjusted R Squared = .076)

Form

Dependent Variable: HatMoved

Form	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C	2642.353	176.875	2294.677	2990.028
F	4129.686	176.875	3782.010	4477.361

The following corresponds to the 1-way ANOVA of physical movement of the body on compare tasks.

Tests of Between-Subjects Effects

Dependent Variable: TorsoMoved

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	215391069.9[a]	1	215391069.88	38.272	.000
Intercept	3500196996	1	3500196996.3	621.928	.000
Form	215391069.9	1	215391069.88	38.272	.000
Error	2352493038	418	5627973.775		
Total	6068081104	420			
Corrected Total	2567884108	419			

a. R Squared = .084 (Adjusted R Squared = .082)

Form

Dependent Variable: TorsoMoved

Form	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C	2170.707	163.707	1848.916	2492.498
F	3602.958	163.707	3281.167	3924.749

The following corresponds to the 2-way ANOVA of horizontal body turns on compare tasks.

Tests of Between-Subjects Effects

Dependent Variable: TorsoTurned_LR

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	21768.314[a]	13	1674.486	1.832	.037
Intercept	114747.428	1	114747.428	125.538	.000
Form	13636.525	1	13636.525	14.919	.000
Region	2481.961	6	413.660	.453	.843
Form * Region	5649.828	6	941.638	1.030	.405
Error	371103.093	406	914.047		
Total	507618.835	420			
Corrected Total	392871.407	419			

a. R Squared = .055 (Adjusted R Squared = .025)

1. Form

Dependent Variable: TorsoTurned_LR

Form	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C	22.227	2.086	18.126	26.328
F	10.831	2.086	6.730	14.932

Insight Task Statistics

The following corresponds to the 1-way ANOVA of physical movement of the head on insight tasks.

Tests of Between-Subjects Effects

Dependent Variable: HatMoved

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	79326743.668[a]	1	79326743.668	47.188	.000
Intercept	812634911.5	1	812634911.48	483.396	.000
Form	79326743.668	1	79326743.668	47.188	.000
Error	425317319.9	253	1681096.126		
Total	1307661463	255			
Corrected Total	504644063.5	254			

a. R Squared = .157 (Adjusted R Squared = .154)

Form

Dependent Variable: HatMoved

Form	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C	1227.648	113.717	1003.696	1451.600
F	2343.363	115.969	2114.976	2571.750

The following corresponds to the 1-way ANOVA of physical movement of the body on insight tasks.

Tests of Between-Subjects Effects

Dependent Variable: TorsoMoved

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	47552995.285[a]	1	47552995.285	33.763	.000
Intercept	610925656.9	1	610925656.92	433.763	.000
Form	47552995.285	1	47552995.285	33.763	.000
Error	356333139.6	253	1408431.382		
Total	1008378382	255			
Corrected Total	403886134.9	254			

a. R Squared = .118 (Adjusted R Squared = .114)

Form

Dependent Variable: TorsoMoved

Form	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
C	1116.212	104.087	911.224	1321.199
F	1980.050	106.148	1771.003	2189.096

Vita

Lauren Marcy Shupp completed her Bachelor of Science in Computer Science from North Carolina State University in Raleigh, North Carolina in 2004. Continuing her studies in the Department of Computer Science at Virginia Polytechnic Institute and State University, she went on to earn her Master of Science in Computer Science with a focus in Human Computer Interaction in Information Visualization in 2006.