The Effects of Peripheral Vision and Physical Navigation on Large Scale Visualization

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Abstract

Large high-resolution displays have been shown to improve user performance over standard displays on many large-scale visualization tasks. But what is the reason for the improvement? The two most cited reasons for the advantage are (1) the wider field of view that exploits peripheral vision to provide context, and (2) the opportunity for physical navigation (e.g. head turning, walking, etc.) to visually access information. Which of these two factors is the key to advantage? Or, do they both work together to produce a combined advantage? This paper reports on an experiment that separates peripheral vision and physical navigation as independent variables. Results indicate that, for most of the tasks tested, increased physical navigation opportunity is more critical to improving performance than increased field of view. Some evidence indicates a valuable combined role.

Keywords: human-computer interaction, geospatial and multidimensional visualization, large high-resolution displays.

Index Terms: H.5.2 [User Interfaces] Ergonomics, Evaluation/methodology

1 Introduction

Larger high-resolution displays, such as tiled wall-size displays (see Figure 1), that contain many more pixels than standard desktop displays have repeatedly been shown to improve people's performance and accuracy on a range of tasks. They show performance improvements for both general office productivity tasks [10][17] and for visualization tasks [3][4][5][6][11][15][16].

What are the fundamental reasons for this advantage? In human interface terms, two primary factors are typically cited:

• *Peripheral vision*: The wider field of view and greater number of pixels of such displays better exploit the human visual field, including both focal and peripheral vision. Standard desktop displays emphasize focal vision, and provide only minimal peripheral area. Larger high-resolution displays provide greater peripheral area, while maintaining the fidelity of the focal area, thus utilizing more of the human 'brain pixels' [21]. In terms of visualization, the key benefits of exploiting peripheral vision are the greater amount of simultaneously visible information, broader contextual overview, and spatial orientation awareness [6][12][14]. For example, Czerwinski, *et al.* show that the greater field of view helps with optical flow and virtual navigation [11].

• *Physical navigation*: The greater area of display, all at high-resolution, better exploits the human ability to physically navigate a visual space. Physical navigation is physical movement of the focal vision to access different portions of the display, such as eye saccades, turning the head, leaning the torso, walking, etc. In contrast, *virtual navigation* involves manipulating the display via input devices such as a mouse or keyboard to bring information into view. Standard desktop displays emphasize virtual navigation, since there is limited opportunity for physical navigation. By measuring both types of navigation, Ball *et al.* show that the increased physical navigation with larger high-resolution displays and the subsequent decrease in virtual navigation correlate with better user performance [5]. The key benefits of exploiting physical navigation over virtual navigation are its physical efficiency (especially eye and head movements), its cognitive efficiency as a user interface, and its natural learnability [2][3][4][7][14].

Furthermore, some point out that the effect may be the result of the combination of both factors:

• *Embodied interaction*: In general, the theory of embodied interaction [12] indicates that the *combination* of human embodiment resources – of which peripheral vision and physical navigation are two – produces the impact. That is, the whole is greater than the sum of the parts. For example, while [5] indicates clear advantages of physical navigation, they also suggest that peripheral vision as an important guiding mechanism for physical navigation producing better overall navigation strategies.

Figure 1. 100 MP 50-monitor display condition that allows both physical navigation and peripheral vision. The total resolution of the display is 16000 X 6000 (96,000,000 pixels).

Though the previous studies indicate some evidence for either factor, they all conflate the two factors. What has not been previously studied is if the improved performance is due more to peripheral vision or physical navigation, or a combination of the two. This opens the research question: Which of these two factors is the key to the advantage? Is one more important than the other, or do they both contribute equally? Or, do they both work together to produce a greater combined advantage? Understanding exactly what improves user performance can help researchers and designers focus their efforts on effective user interface design approaches, and lead towards improved theories for visualization and interaction with large displays.

Thus, in this paper we report on a study that directly addresses this issue by separating the two factors – peripheral vision and physical navigation – as independent variables, to determine how each individually and interactively effect user task performance. We conducted a controlled factorial experiment to isolate the two independent variables. We tested the factors on a variety of visualization tasks (navigate, compare, search, pattern, estimation) on a large 2D geo-referenced data visualization, and measured users' task performance time and accuracy.

It is important to understand that in this study we explored this issue within the practical context of using current-day large high-resolution displays, not as a pure psychological issue. In other words, we studied how physical navigation and peripheral vision effect performance *only* in the context of using large displays, not as a general psychological phenomenon.

Based on previous evidence, our hypothesis was that peripheral vision and physical navigation would have approximately equal significant effect in terms of performance, and that an interaction effect would indicate a multiplicative combined advantage. However, we show that our hypothesis was incorrect. Instead, for most of the tasks tested, physical navigation had a much greater impact towards faster user task performance time than did peripheral vision.

2 Related Work

Larger displays containing more pixels have been shown to produce better user performance than smaller displays under a variety of conditions.

More pixels: Swaminathan and Sato [19] were among the first researchers to report on the differences between single versus multiple monitors. Their conclusions have since been validated by other researchers. Their most important contribution is that multi-displays are qualitatively different from single monitors. They explain that new interaction techniques and methods are needed to adapt to the larger displays.

In addition, Simmons [17] conducted a study comparing performance on different-sized monitors (17 inch to 21 inch), with slightly differing resolutions. People performed fastest with the largest monitor that had slightly higher resolution, in comparison to the smaller monitors.

Czerwinski, *et al*. [10] conducted a study showing conclusively that participants using a multi-monitor configuration affording increased resolution (3 monitors wide) performed better than on a single monitor. Czerwinski, *et al.* later showed that the effects of an increase of field of view (greater use of peripheral vision) can offset the gender bias that exists in virtual navigation [11].

Sabri, *et al.* [15] showed how larger displays can affect game play. In their study, expert gamers played against each other on different sized displays. The larger sized displays (3x3 tiled monitors) affected the players' strategies and resulted in more wins and greater enjoyment for the players.

Ball, *et al.* [3] investigated visual search performance on large high-resolution displays. Although users were seated, they observed some physical navigation (head turning, leaning, standing up) even though virtual navigation controls (pan & zoom) were also provided. In a follow up study, Ball and North [5] investigated how motivated users perform physical navigation with large displays while standing and walking. Users had up to 10-fold improvement in performance time with larger displays when using physical navigation over virtual navigation.

Mixed density displays: Baudisch, *et al.* [6] performed an experiment using a "Focus plus Context Screen" to study the effects of having a small LCD screen embedded within a large projection screen (both standard low-resolution) to take advantage of peripheral vision. In effect, they created a focus+context visualization using pixel density distortion instead of magnification distortion. They conclusively showed that participants performed better while using their mixed-density display than with standard monitors.

Similarly, but with a different twist, Ashdown, *et al.* [1] created a mixed density display for the desk. By combining a number of different projectors from different angles they were able to have different pixel densities at different areas of the desk with the highest density of pixels in the middle of the desk.

We use these principles to create our own simulated focus+context screen for one of our experiment conditions. Unlike their displays, we created our display by using software techniques to adapt a large high-resolution display.

Curved displays: Shupp, *et al.* [16] created a reconfigurable display out of tiled LCD monitors that can be curved horizontally at any angle, using autonomous stands that can be moved independently of each other. Shupp's experiment results showed that curving the display around the user, versus a flat display, improved user performance on various visualization tasks. By having a large curved display, users could better exploit their peripheral vision and physically navigate by simply turning their head. Starkweather, *et al.* [18] created a seamless curved projection-based multi-monitor display called DSHARP using DLP projectors and parabolic mirrors.

3D virtual environments: Bowman, *et al*. [7] showed that users in a 3-wall CAVE chose virtual rotations more often than HMD (Head Mounted Display) users for the same task (maze traversal), and that HMD users tended to outperform CAVE users. They hypothesize that this is due to the increased 360-degree physical navigation that HMD users had, where CAVE users could not (due to the missing back wall), despite the more limited field of view of the HMD.

The trend towards better performance with physical navigation has been confirmed by a number of researchers. The use of head tracking in immersive information visualizations was preferred by users and also appeared to improve comprehension and search [12]. Similarly, Pausch, *et al.* [13] showed that users of a head-tracked HMD took less time to indicate that a target was not present in a visual search task as compared to users of the same display when a handheld tracker controlled the viewpoint. Chance, *et al.* [9] demonstrated that when users physically turn and translate, they maintain spatial orientation better than when they virtually turn and translate. Bakker, *et al.* [2] found that subjects could more accurately estimate the angle through which they turned if provided with vestibular feedback.

In conclusion, the related literature shows that there have been a number of experiments and studies that show that increased use of peripheral vision and/or physical navigation with large displays improves performance time with a number of tasks. However, what is not known is how peripheral vision and physical navigation independently affect performance.

3 Experimental Design

The goal of this experiment was to determine the effect of peripheral vision and physical navigation on users' visualization task performance in a large 2D information space. The task domain involves navigating and finding information in a large 2D geospatial visualization containing embedded quantitative multi-dimensional data (described further in 3.2). Peripheral vision and physical navigation are tested by developing four display conditions that the subjects used to navigate the visualization.

As a guiding philosophy in the experiment design, this experiment seeks to examine peripheral vision and physical navigation within the practical context of using large high-resolution displays, not as a pure psychological issue. There are tradeoffs in the choice of experimental design, and it is difficult to eliminate all possible confounds. For example, physical navigation allows for a continuous spectrum of visual pixel density by stepping closer or further away from the display, whereas pixel density is constant with virtual navigation based on the constant distance the person sits away from the display. From a pure psychological point of view, one might attempt to use different types of displays (e.g. HMD, different resolution displays, bezel-less displays, etc.) to help isolate physical navigation and field of view. If we had used another display (such as HMD) to control for constant pixel density while allowing for physical movement, the study would not be as relevant for research on large displays. Furthermore, different types of displays introduce other confounding factors.

Hence, we chose to take the practical approach and emphasize large display usage. This practical approach allows us to conclude, for example, that physical navigation, along with its many other benefits and/or drawbacks that may or may not be identifiable, is better than virtual navigation with its many other benefits and/or drawbacks. In essence, this study allows a practical answer to the basic question of whether peripheral vision or physical navigation has a greater benefit for large high-resolution displays.

3.1 Experimental Conditions

The two independent variables are peripheral vision and physical navigation. Each variable has two levels. The 2x2 design creates 4 experimental conditions as shown in Table 1. The conditions are tested by designing a specific display setup for each condition on which to display the visualization.

1. Peripheral Vision: This variable indicates the amount of peripheral vision exploited by the display. A continuous range is possible, but we narrow to two levels:

a. Context: Allowed participants to use at least 140 degrees of their field of view to see the visualization, by utilizing a large display.
b. Focus: Limited participants to approximately 30 degrees of their field of view (the equivalent of viewing a 20" 2 MP display from a distance of three feet).

We chose to define these levels from a practitioner's point of view, thinking in terms of a typical desktop display as the Focus condition, as opposed to the physiological definition of human visual focus, which is quite small.

2. Physical Navigation: This variable indicates the amount of physical navigation opportunity offered by the display. A continuous range is possible, but again we narrow to two levels:

a. Physical: Allowed participants to freely move over a large 100 MP (MegaPixels) 15'x6' display. This allowed natural movement of walking, turning the head, twisting the torso, crouching, etc. The visualization was sized to exactly fit this display, so that virtual navigation was not allowed in this level.
b. Virtual: Limited participants to a sitting position in which they were asked not to lean forward or turn their head beyond what is necessary to see the central 2 MP 20" display. Virtual navigation (zoom+pan) was thus required to access all details of the visualization.

Table 1. Four conditions of peripheral vision and physical navigation. Previous studies examined only the main diagonal (Yes-Yes vs. No-No).

		Peripheral Vision	
		Yes: "Context"	**No: "Focus"**
Physical Navigation	**Yes: "Physical"**	100 MP 50-monitor display	100 MP with blinders
	No: "Virtual"	Focus + Context display	2 MP 1-monitor display

Again, we define these levels form a practitioner's point of view. We define the physical navigation condition to be physical movement beyond that performed in regular use with a typical single desktop monitor. Thus, the 'limitation' levels for both the peripheral vision and physical navigation variables are defined based on the same standard 20" 2MP display (with a resolution of 1600 X 1200). This provides a common standard, without biasing towards either variable, in comparing to the largest display. Note that this also creates consistency with prior studies that examined the main diagonal of Table 1 (Yes-Yes vs. No-No conditions). By adding the other two corners, we are able to separate out the peripheral vision and physical navigation factors.

3.1.1 CP: Context-Physical condition (100 MP display)

In order to test for both peripheral vision *and* physical navigation we used a display with approximately 100 MP - a 50-monitor display wall – constructed of twenty-inch (50.8 cm) monitors (see Figure 1). The total resolution of the display is 16000 X 6000 (96,000,000 pixels). The physical dimensions of the display were 14.58 feet (4.4 m) tall by 5.58 feet (1.7 m) wide with the lowest part of the display being 1.6 feet (0.5m) off the ground. Twenty-five Linux-based computers drove the display.

In order to isolate physical navigation from virtual navigation we created a data set that used the entire display space of the large display without need for virtual navigation. In other words, participants could see all the data by physically moving - such as walking or turning their head - without having to use a mouse, or any other input device. All participants stood during the physical navigation conditions; a chair was provided during breaks between tasks if needed.

Although the use of virtual navigation in conjunction with physical navigation has many advantages (e.g. [3]), the point of this condition was to isolate physical navigation from virtual navigation as much as possible in a controlled setting. Thus, virtual navigation was disabled.

Figure 2. One monitor condition that does not offer physical navigation or peripheral vision.

3.1.2 FV: Focus-Virtual condition (2 MP, single monitor)

In order to test *without* peripheral vision *and without* physical navigation we used only a single monitor of the above wall display (Figure 2). The visualization, which was sized according to the 100 MP display, was zoomed out in its initial state. To access all details, users would need to zoom and/or pan the visualization using standard mouse controls -- "sticky hand" interaction for panning and mouse wheel for zooming similar to Google Maps.

3.1.3 FP: Focus-Physical condition (100MP with blinders)

In order to test for physical navigation *without* peripheral vision we used the same 100 MP display as the Context-Physical condition, with the addition of requiring participants to wear blinders that create a tunnel-vision effect. The blinders were created by using poster board and splashguard goggles. The blinders limited the participants' field of view to approximately a single 2MP monitor size when standing three feet (0.91 m) from the display, and thus equivalent to the Focus-Virtual condition in terms of peripheral vision. Figure 3 shows an example of a participant with blinders using the large display. As with Context-Physical, virtual navigation was not allowed in this case, only physical navigation.

Figure 3. '100 MP display with blinders' condition that allows physical navigation but not peripheral vision.

3.1.4 CV: Context-Virtual condition (Focus+Context)

In order to test peripheral vision *without* physical navigation we used a twenty-five (25) monitor focus plus context display based on Baudisch, *et al*'s prototype [6] (see Figure 4). A focus plus context display has a center that is high-resolution and detailed, surrounded by a low-resolution context.

To match the Focus-Virtual condition, users were seated and asked to focus only on the center monitor (the focus monitor) and were thus required to virtually navigate to access all details. The purpose of using the low-resolution context was to mimic the reduced resolution of human peripheral vision, and thereby inhibit any benefit users would gain by cheating and looking outside the focus area (illegal physical navigation). By requiring participants to only look directly at the focus monitor we were able to test use of peripheral vision without physical navigation. In effect, we tested participants on a single monitor with a peripheral aide.

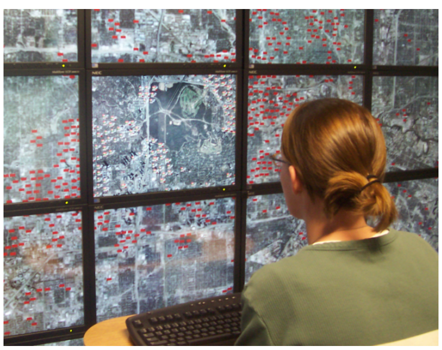

Figure 4. 25-five monitor Focus+Context display condition that allows peripheral vision but not physical navigation. The center monitor (the monitor the participant is looking at) is high-resolution, while the surrounding 24 monitors are low resolution.

Figure 5 shows a screenshot example of what the visualization looks like at the transition from focus to context. This transition appears to be somewhat natural to the user as it occurs at bezel borders of the focus monitor.

Baudisch created a focus plus context prototype display through a combination of displays of different resolutions. We simulated the effect by software rendering on a high-resolution display. We used twenty-five monitors, as opposed to all fifty, to maximize the interactive performance of the display, and were still beyond the 140-degree visual angle goal. The virtual navigation speed was approximately the same as the single monitor condition.

The reader should note that the experiment did not compare the utility of a Focus+Context Screen against other displays, because the experiment required participants to maintain their eye gaze solely on the focus, middle monitor. This was done so that the context part of the display – the other 24 monitors – would act only as peripheral vision aide. Normal usage of a Focus+Context Screen would allow users to look at any part of the display.

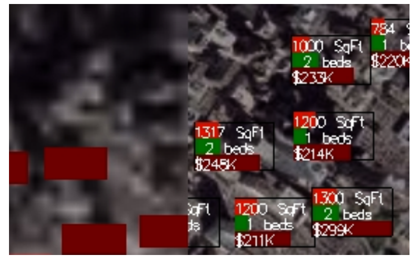

Figure 5. Screenshot example of the transition of focus (details) on the right and context (blurry surrounding area) on the left.

At the beginning of each task all participants started at the same physical location according to the condition. In other words, all participants started at the same standing position for the physical navigation conditions and all participants sat in the same location for the virtual navigation conditions. In both cases, the user started in the zoomed out position, either physically or virtually.

3.2 Data and Visualization Explanation

We created a visualization of 1,924 houses for sale in Houston, TX. The visualization displayed data about the houses on a map of the Houston area using geometric zooming. Figure 5 shows an example of what the visualizations looked like. The right side of the image shows how the house visualizations appeared in all conditions and in the focus part of the focus plus context display. The left side shows how the house visualizations appeared in the context part of the focus plus context display.

The house visualizations showed the square feet (top bar), the number of bedrooms (middle bar), and the price in thousands of dollars (bottom bar). Each attribute showed both text and a normalized bar chart based on the maximum of that particular attribute. For example, the bar chart for price was completely filled when the house was for sale at $300,000.

The reason for geometric zooming over semantic zooming was to ensure that all the conditions saw the same visualizations in the same way. Our reasoning is that for the physical navigation conditions – the conditions that used the fifty monitor display – the data was out of necessity static. As a result, semantic zooming was not possible without creating a new semantic zooming technique that works for physical navigation.

We used a modified version of the NCSA TerraServer Blaster [20], an application that views images from US Geological Survey. Specifically, we modified the application by adding superimposed data visualizations to the base map, providing mouse interaction, and added the focus+context ability.

3.3 Tasks

The participants performed the following tasks:

1. Navigation to a target (repeated 4X)
2. Comparison of targets (repeated 3X)
3. Search:
    a. by data attribute value (repeated 2X)
    b. by geospatial feature (1X only)
4. Pattern finding for a group of targets (repeated 3X)
5. Estimation:
    a. of price (accuracy) (1X only)
    b. of square footage (accuracy) (1X only)

To measure only performance time and not accuracy for the first four tasks, participants were asked to keep working until the task was completed correctly. For example, in the pattern task subjects searched for the pattern until they reported it correctly.

For the navigation task, a single house was shown on the display. Participants were asked to verify that they could see the house before proceeding. This was done to ensure that participants were not being asked about their ability to find the house. After verifying the presence of the house, they were then asked for an attribute about the house (e.g. its price). The task was complete when they spoke aloud the correct corresponding attribute value of the house. This might require navigating (e.g. zooming) to the house to see the textual attributes. The Comparison task involved navigating to two target houses and comparing their attributes.

There were two types of search tasks. The first involved finding a house that met an attribute value criteria (e.g. find a house priced between \$100,000 and \$110,000). There was not a unique correct answer per task as several houses fit each criterion. Approximately the same numbers of houses were potential correct answers for each task. The second type of search task involved finding a geospatial object such as a golf course, airport, stadium, etc. Examples of similar geospatial objects were shown to the participants in color on paper before the task. For example, before they were asked to find a golf course, example golf courses that were not part of the base map were shown to the participant.

Pattern finding tasks required participants to identify patterns for all the displayed houses. For example: "Where is the cluster of most expensive houses?" Each pattern finding task had a unique correct answer; participants did not have any difficulty arriving at the answer once the correct information was in view.

There were two estimation tasks: Find the average price and find the average square footage of the houses for sale. Participants were told to take as long as they needed to arrive at the best estimate they could; accuracy, not time was stressed.

3.4 Participants

The experiment had 24 participants (9 females and 15 males). 4 were undergraduate students and 20 were graduate students. All the participants were computer science majors or had considerable computer science. The ages of the participants ranged from 20 to 36 with an average age of 25.6. None of the participants were colorblind nor had prior familiarity with Houston, Texas.

In order to motivate the participants, fifty dollars (\$50) was given to a participant if they had the fastest average performance time in a task category. Performance time was calculated based on how long it took the participant to reach the correct answer. Since there were four tasks where performance time was measured, each participant had four tries to win a prize.

3.5 Design and Protocol

The independent variables for the experiment were physical navigation (yes/no) and peripheral vision (yes/no). The dependent variable was performance time or accuracy of estimation.

The Navigation, Comparison, and Search tasks were with-in subject and the Pattern and Estimation tasks were between subjects. The latter tasks were between subjects due to the limited number of patterns and estimations that could be performed on the dataset. We used a balanced Latin Square design to determine the ordering of conditions the participants would be exposed to.

Prior to the first task, all participants were given at least five minutes to familiarize themselves with the visualizations and what they meant. Prior to the first task on the first virtual navigation condition (one monitor or focus+context) participants were given at least five minutes to familiarize themselves with the virtual navigation controls.

Each task began with the overview/best-fit of the map always showing the same area of Houston. The aspect ratio of the base map was preserved so that each condition initially showed the same total overview area, but with different amounts of detail.

For the virtual navigation conditions (one monitor and focus+context) this meant seeing a zoomed out view of the Houston area at the beginning of the task. For the physical navigation tasks this meant being approximately 15.5 feet (4.72 m) away from the display to see the same area and aspect ratio.

4 Experiment Results

To understand how peripheral vision and physical navigation affected performance we ran a two-way ANOVA on performance time with physical navigation and peripheral vision as factors with two levels each (as in Table 1) (this excluded the estimation tasks). We found a main effect of physical navigation ($F(3,956)=4.72$, $p<0.001$) but did not find a main effect of peripheral vision or an interaction.

This result was surprising since we had hypothesized that both physical navigation and peripheral vision played equal and multiplicative roles in the performance boost of large displays. However, in general, it appears that peripheral vision did not have a significant impact on performance for the tasks performed.

4.1 Navigation and Comparison Tasks

We performed a series of post-hoc two-way ANOVA's with physical navigation and peripheral vision as factors on the individual tasks to understand how physical navigation and peripheral vision affected each task in turn. The navigation and comparison tasks were designed to measure efficiency of information access. For the navigation task we found a main effect of physical navigation ($F(1,380)=189.99$, $p<0.001$) and an interaction of physical navigation and peripheral vision ($F(1,380)=3.77$, $p=0.05$) (see Table 2 and Figure 6).

A possible interpretation of these results is that navigation is affected by physical navigation, and that the effect is amplified by peripheral vision. This interaction explains why the fifty-monitor condition outperformed the fifty-monitor plus blinders condition.

Table 2. Average performance time, in seconds, for the Navigation tasks (with standard deviations).

		Physical navigation		
		yes	No	
Peripheral vision	yes	3.3 (0.6)	7.6 (2.5)	5.4 (1.6)
	no	3.8 (0.9)	7.5 (1.9)	5.6 (1.4)
		3.5 (0.8)	7.5 (2.2)	

The two-way ANOVA for the comparison task found only a main effect of physical navigation ($F(1,284)=134.21$, $p<0.01$) (see Table 3 and Figure 6). Thus for the comparison task, physical navigation was a significant factor while peripheral vision was not. This was an especially surprising result as most participants commented that the Focus+Context display helped them maintain the spatial position of both houses being compared.

Table 3. Average performance time in seconds for the Comparison tasks (with standard deviations).

		Physical navigation		
		yes	No	
Peripheral vision	yes	3.8 (1.5)	11.3 (5.7)	7.6 (3.6)
	no	4.7 (1.8)	11.9 (8.6)	8.3 (5.2)
		4.3 (1.7)	11.6 (7.2)	

Participants were generally observed to be faster with physical navigation than virtual navigation for both the navigation and comparison tasks. Was the performance difference due to a speed issue in the response time of the display's computing cluster? Possibly, however, the fastest participants with the virtual navigation conditions were as fast as the average participants on the physical navigation conditions. The large differences in times with the virtual navigation conditions (one monitor and focus plus context) can be seen by the error bars, which represent the standard deviation, in Figure 6.

One reason for the large variation in performance times for the virtual navigation tasks can be explained by the difference in virtual navigation abilities of the participants. On one extreme were participants that were able to traverse the virtual space quite well. On the other extreme were participants that easily got lost in tracking objects in the virtual space.

On the other hand, there is much smaller variance for the physical navigation conditions (fifty monitors and fifty monitors with blinders). Even with blinders participants never had trouble losing the location of comparison targets. With the physical navigation conditions participants were better able to keep a reference where targets were, probably by using spatial memory. This was especially important for the comparison task on the fifty monitors with blinders condition. When a participant was examining a particular target in detail the blinders prohibited the participants from seeing the other target. However, participants still had a good general idea of where the second target was using spatial memory and motor memory to quickly re-find it.

Another reason that the comparison task could be performed so quickly occurred when the prices of the houses could easily be visually distinguished from each other. In these cases participants could stand at the starting point, or move slightly closer to the display, to see which bar chart was wider.

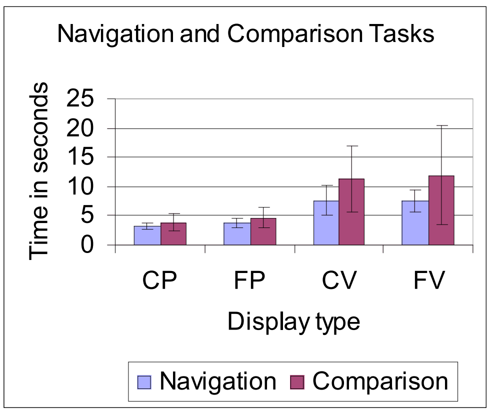

Figure 6. Average performance time for the Navigation and Comparison tasks. The error bars indicate the confidence interval of each condition. Physical Navigation has significant effect.

4.2 Search Tasks

The attribute value search task – searching for houses that meet particular attributes value criteria – resulted in non-significance for both physical navigation and peripheral vision due to very high variance. The second search task involved finding a geospatial feature (e.g. a golf course, airport, etc.), and results found a main effect of physical navigation (F(1,92)=4.59,p=0.03) (see Table 4 and Figure 7). Once again, it appears that physical navigation was significant while peripheral vision was not.

Table 4. Average performance time in seconds for the geospatial feature Search task (with standard deviations).

		Physical navigation		
		yes	no	
Peripheral vision	yes	28.5 (37)	44.0 (52)	36.3 (44)
	no	29.7 (43)	58.2 (64)	43.9 (53)
		29.1 (40)	51.1 (58)	

One possible reason for the physical navigation conditions outperforming the virtual navigation conditions is due to the search strategies employed. Participants were generally observed to use a multi-scale search strategy while physically navigating, but only a two-scale search strategy while virtually navigation. In other words, participants with the physical navigation conditions were observed to freely and actively walk around at different distances from the display. This means that they were freely physically zooming further and closer to the display in order to quickly see more or less overview or detail. This enabled them to look in detail only at areas that held more promise.

Whereas, with the virtual navigation conditions participants were generally observed to pan around at one zoom level and then, if the target was not found, to zoom in once more and perform an algorithmic search strategy of panning around the entire virtual space. After zooming in to see sufficient detail, two different algorithmic search strategies were performed with equal likelihood among the participants. One strategy usually exhibited was panning around in a circular pattern, such as panning the entire perimeter of the Houston area then panning in a circular pattern the interior of the area. The other strategy was panning in a back and forth manner – panning from the left side of Houston to the right side of Houston panning slightly down and then panning back to the left side of Houston again, and so on.

The trends indicate that, in the geospatial search task, peripheral vision was primarily helpful in the virtual navigation condition, not the physical navigation condition. This is opposite from the Navigation and Comparison tasks.

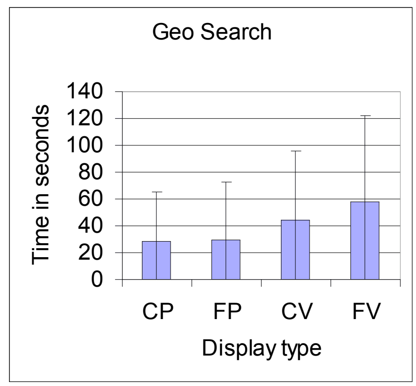

Figure 7. Average performance time for the geospatial Search task, finding objects such as golf courses, stadiums, airports, etc. Physical Navigation has significant effect.

4.3 Pattern Finding Tasks

The pattern finding tasks (e.g. "Where is the most expensive cluster of houses", "Where is the least expensive cluster of houses") resulted in a main effect of physical navigation (F(1,44)=4.13,p=0.04) (see Table 5 and Figure 8). Pattern tasks were designed to represent more complex visual tasks that required broad understanding of the dataset.

Interestingly, peripheral vision appeared to have little effect on participants' ability to find patterns. This is a very surprising result as one might expect participants to rely more on peripheral vision because of the nature of this visualization intensive task.

Table 5. Average performance times in seconds for the Pattern finding tasks (with standard deviations).

		Physical navigation		
		yes	no	
Peripheral vision	yes	31.9 (18)	47.9 (35)	39.9 (26)
	no	31.7 (14)	45.8 (23)	38.8 (18)
		31.8 (16)	46.9 (29)	

For all conditions participants were observed to analyze only naturally occurring clusters of houses at a time. After analyzing one cluster the participants would then analyze adjacent clusters of houses. For the physical navigation conditions, participants would analyze a cluster of houses and remember where that cluster was with respect to the other clusters. Apparently by using spatial memory they were able to organize the different clusters in some sort of order without looking at the same clusters again. In addition, they were apparently able to use external memory in the sense that they could glance back at a cluster and remember what their conclusion about that cluster was. After analyzing all house clusters participants would then recognize a global pattern taking into account all the clusters.

In the virtual navigation conditions, the strategy for finding the patterns was the same in that participants would try to understand individual house clusters first. However, participants were apt to revisit house clusters either because they were not aware that they had been to that exact cluster before due to natural disorientation with virtual navigation or they did not recognize the cluster. Participants might not recognize a cluster for a number of reasons, such as the cluster looked slightly different since the participant might have earlier inspected it at a different scale.

It is particularly surprising that physical navigation, rather than peripheral vision, is the key to enabling this tracking ability and re-visitation avoidance.

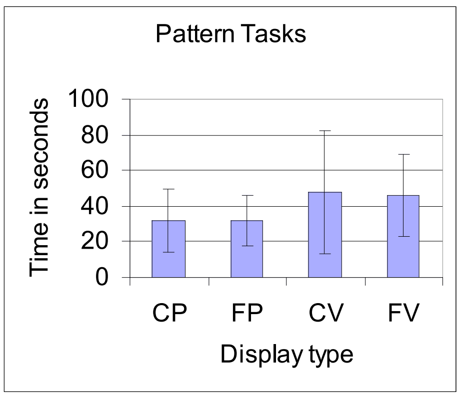

Figure 8. Average performance time for the Pattern finding task. Physical Navigation has significant effect.

4.4 Estimation Tasks

The estimation tasks were the only tasks in which accuracy was measured. Accuracy was measured according to how close the participants' estimated average values were to the actual averages. Similar to the pattern task, the estimation task was designed to represent insightful visualization usage that requires broad understanding of the whole dataset.

The estimation of price task resulted in no main effects of peripheral vision or physical navigation on accuracy, but did result in an interaction ($F(1,20)=10.59, p=0.004$) (see Table 6 and Figure 9). Table 6 shows a textbook example of interaction between peripheral vision and physical navigation.

The actual average price for the houses displayed in the experiment was $153,038. Amazingly, the average estimated price of the one monitor condition was $154,000. The addition of peripheral vision or physical navigation appeared to cause participants to overestimate. However, having both peripheral vision and physical navigation resulted in less overestimation.

The estimation of square footage task resulted in a main effect of peripheral vision ($F(1,20)=4.76, p=0.04$) (see Table 9 and Figure 10). For this task it appears that the additional field of view led to overestimation. The actual average square footage was 1,673 square feet. The average estimation for the 50-monitor with blinders condition was amazingly only 10 square feet off from the actual answer and the one monitor condition was only 94 square feet off from the actual answer.

One possible explanation for the overestimation with peripheral vision is that the longer bars in the bar charts give more visual weight and emphasis to the more expensive or larger houses. Thus, with a wide field of view of the visualization, the longer bars dominate and give the impression of higher average values.

Table 6. Average difference in dollars of price estimations from actual answer for the Estimation of Price task (with standard deviations).

		Physical navigation		
		Yes	no	
Peripheral vision	yes	+$18,629 ($18,074)	+$36,129 ($11,143)	+$27,379 ($14,608)
	no	+$39,629 ($24,590)	+$962 ($29,563)	+$20,295 ($27,076)
		+$29,129 ($21,332)	+$18,545 ($20,353)	

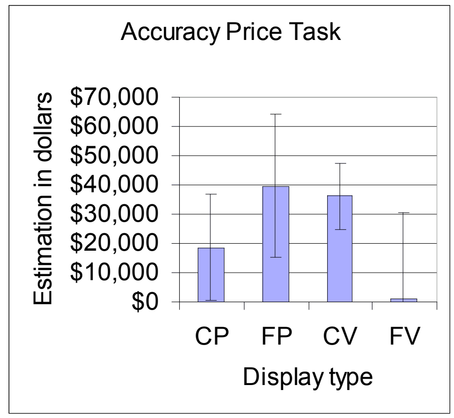

Figure 9. Average difference in dollars of price estimations from actual answer for the Estimation of Price task, with significant interaction effect.

Table 7. Average difference in sqft of square-footage estimations from actual answer for the Estimation of Square Feet task (with std deviations).

		Physical navigation		
		yes	no	
Peripheral vision	yes	+260.3 (294)	+243.7 (232)	+252 (263)
	no	+10.3 (121)	+93.7 (216)	+52 (168)
		+135.3 (207)	+168.7 (224)	

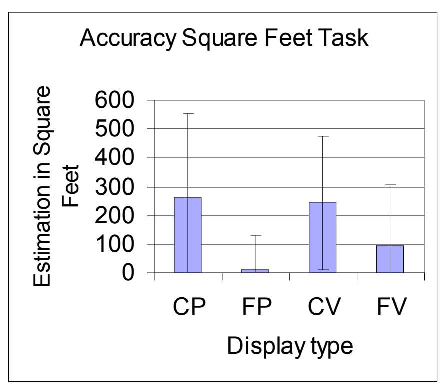

Figure 10. Average difference of square-footage estimations from actual answer for the Estimation of Square Feet task. Peripheral vision has significant effect.

Interestingly, it took participants in different conditions different average amounts of time to decide on an answer they felt good about. For both estimation tasks the participants on the fifty-monitor condition took approximately half the time as the other conditions. The participants for the other conditions took approximately the same amount of time. Running a two-way ANOVA on the performance time resulted in non-significance.

5 Display Condition Preferences

After the completion of the experiment, participants were asked to indicate which of the display conditions they preferred. One participant chose the one-monitor condition, one participant chose the 50-monitors with blinders, two chose the focus+context display, and the other twenty participants chose the 50-monitor condition (with both physical navigation and peripheral vision).

The most cited reason for preferring the 50-monitor condition was the freedom to physically navigate to see all the data at once. Participants explained that they were able to freely see any part of the data with ease. The participants that preferred the focus+ context condition or the one monitor condition cited the required physical navigation as the reason they did not like the 50-monitor condition. The participant that preferred the 50-monitors with blinders condition indicated that the blinders helped them not to be distracted by the rest of the display when looking at details.

6 Conclusion

The experiment reported here helps answer the question of how peripheral vision and physical navigation affect performance time and accuracy for 2D geospatial visualization tasks on large high-resolution displays. Overall, physical navigation had a main effect for performance time and peripheral vision did not.

It appears that the behavior of the participants was not equally affected by the two independent variables. Specifically, it appears that behavior was most affected by physical navigation, and participants were observed to employ different strategies when using physical navigation or virtual navigation. For example, in the search tasks participants were observed to use more algorithmic strategies with virtual navigation and more multi-scale or free flowing strategies with physical navigation. Different overall strategies were not observed between different levels of the peripheral vision independent variable.

That is not to say the peripheral vision did not help. In fact, there were cases where there was an interaction of both physical navigation and peripheral vision that led to the best performance times. These interaction effects may be evidence for embodied interaction, where physical navigation and peripheral vision work together to amplify the individual effects.

One could theorize that the reason the 100 MP condition uniformly had the best performance times was because of the natural way in which participants were able to interact with the data. By physically navigating, participants were able to take advantage of many of their embodied cognitive resources (e.g. spatial memory, optical flow, etc.).

While physical navigation promotes higher order thinking, such as investigating data points that hold the most promise for solving a task, virtual navigation promotes more simplistic algorithmic strategies that are less efficient. The same participants that were more efficient in search and navigation strategies for physical navigation were less efficient with virtual navigation. Why?

One possible reason is that when using virtual navigation participants had a much higher cognitive load in trying to orient themselves in the virtual space. Participants were repeatedly observed to get confused or lose their way with virtual navigation, even with the peripheral context. However, with the physical navigation conditions participants were never observed to be lost or disoriented, even in the blinders condition.

How does this affect visualization design? These results may indicate that designs that stress physical navigation will be more successful, even if peripheral vision is not available. For example, large multi-scale visualizations should embed small details directly into broad overviews. Also, one might suspect that approaches based on HMDs might fair better than purely focus+context screens. To date, HMD's have shown limited success in studies, but may be due to other factors such as lag, shielded view of the physical world, etc.

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