Beyond Visual Acuity: The Perceptual Scalability of Information Visualizations for Large Displays

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ABSTRACT
The scalability of information visualizations has typically been limited by the number of available display pixels. As displays become larger, the scalability limit may shift away from the number of pixels and toward human perceptual abilities. This work explores the effect of using large, high resolution displays to scale up information visualizations beyond potential visual acuity limitations. Displays that are beyond visual acuity require physical navigation to see all of the pixels. Participants performed various information visualization tasks using display sizes with a sufficient number of pixels to be within, equal to, or beyond visual acuity. Results showed that performance on most tasks was more efficient and sometimes more accurate because of the additional data that could be displayed, despite the physical navigation that was required. Visualization design issues on large displays are also discussed.

Author Keywords
Information visualization, large displays, visual acuity

ACM Classification Keywords
H.5.2 Information Interfaces: User Interfaces – Evaluation/Methodology

INTRODUCTION
Display technology has been decreasing in cost [1] which makes large, high resolution displays (Figure 1) a more viable option for single users. This option is particularly beneficial for people in organizations such as NASA [19], AT&T [2, 29], and other research labs [15] that have large datasets and make heavy use of information visualizations because the scalability of visualization has been mostly limited by the number of pixels [12]. Theoretically, any size dataset can be visualized on a display with an infinite number of pixels.

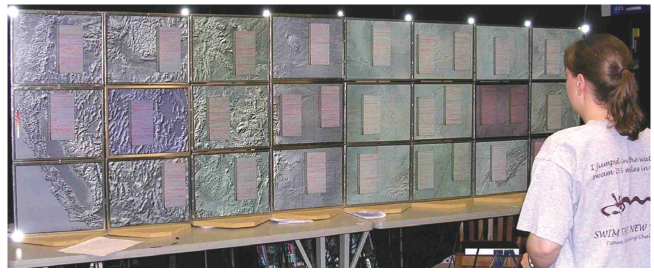


Figure 1. Large, high resolution display (~32 Mp).

Using large, high resolution displays means that graphical scalability (the number of pixels required to visualize a dataset) is less of a limitation. When graphical scalability is no longer an issue, then what scalability limits may exist due to human abilities? One possibility is that visual acuity imposes a perceptual scalability limit. If the dots per inch (DPI) of a display is so high that an individual pixel cannot be seen, regardless of how close a user is to a display, then an even higher DPI is unlikely to be beneficial. More interesting is the situation where pixels are of a sufficient size, the DPI is constant, and the number of pixels is increased using a larger display. This can result in a total display resolution such that the user cannot see all of the pixels from any particular location without walking. In this case we refer to the display as being beyond visual acuity. This has led to the argument that a display with a resolution equal to visual acuity should be adequate for any single user visualization task [27, 28].

In this paper we explore the influence of using a display with enough pixels to exceed visual acuity when scaling up information visualizations. We present an experiment that compared two different visualization designs that were scaled up to larger datasets (with data density kept constant) using display sizes with enough pixels to be within, roughly equal to, and beyond visual acuity.

RELATED WORK

Benefits of Display Size, DPI, and Field of View
Research on the use of large displays has shown a variety of cognitive and user performance benefits [9, 10]. Some of these benefits are likely due to the increased field of view resulting in the creation of better cognitive maps. This is evident by large displays resulting in better performance for 3D navigation tasks [23] and leading to less reliance on way

finding aids [16]. This also applies to 2D information, where map navigation is faster and more accurate when using large displays [5]. Additionally, there is research showing that spatial ability differences due to gender are narrowed when using larger displays because of better optical flow cues [11]. Even when high resolution is not maintained in the periphery of a display, there are performance benefits due to the increased field of view [6].

In addition to the advantages of a wider field of view, there also seem to be advantages to information being physically larger and at a higher DPI. When the visual angle is held constant, simply having a larger display compared to a smaller display improved performance on spatial tasks despite increased viewing distance [24, 25]. When the display size was increased and the DPI remained the same, using a larger display improved 3D task performance by making abstract information more visible [16] and allowing for an increased software field of view [17].

While there appear to be many advantages to using large, high resolution displays, none of these studies considered a display of sufficient size and resolution to go beyond the limits of visual acuity - the largest display was less than 5 megapixels (Mp) in width.

Physical Navigation

Typically, information visualizations deal with the graphical scalability limits of desktop monitors by using techniques such as aggregation, elimination, or virtual navigation. Given an unlimited number of pixels, these techniques can be traded for physical navigation. One study showed that for a basic visualization task, physically navigating was faster on a 10 Mp display than panning and zooming on a smaller display [4]. Performance can further be improved if less strenuous physical navigation is required. This can be accomplished by curving the display to bring the outermost pixels closer to the user [21]. That study found performance benefits for a basic route tracing task but not for a basic search task.

Human Vision and the Optimal Display

While brightness, color, and misalignment of images are important issues [3], the most debated issue with large, high resolution displays deals with visual acuity [20]. The question is if pixels are wasted when using higher resolutions in the periphery on large displays [22]. Ware asserts that a 4000x4000 display is the optimal display because it is most efficient at matching screen pixels to the “brain pixels” that interpret the signals sent by photoreceptors in our eyes [27]. He suggests that this type of display is adequate for any visual task.

There is some research that supports the idea that there may be performance costs if visualizations are scaled up using larger displays. The most relevant research deals with the eccentricity effect, which shows that performance gradually degrades as a target gets farther from our point of visual fixation and that the extent of this effect increases with larger set sizes [7]. With larger displays more details will be farther away and therefore performance may decrease due to the eccentricity effect. Using the additional pixels to scale up the amount of simultaneously visible information will increase the set size and may thereby exacerbate the problem. Additionally, our visual field is reduced to 92% under medium mental workload and to 86% under heavy mental workload [18]. This may mean that additional data could lead to more mental workload and thereby a user being able to see less information. However, one experiment evaluating user performance on text-based tasks found that visual separation only hurt performance when combined with an offset in depth [25]. That study did not scale up the amount of information and only made use of two monitors that were placed next to each other. Again, none of these studies used a display that had a resolution that exceeded visual acuity.

Perceptual Scalability of Visualization

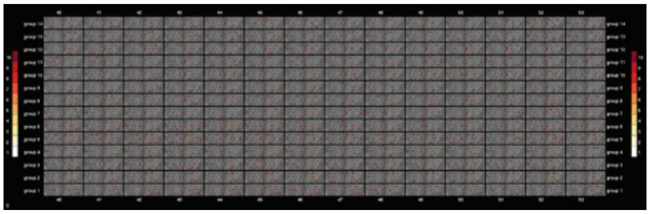
In a study preceding this work, we explored the perceptual scalability of different visualization designs when scaled up using a larger display. We compared three different visualizations either on a 2 Mp display with approximately 250 data points, or scaled up to a 32 Mp display with approximately 5,000 data points [31]. Overall, there was no significant decrease in accuracy and a 20x increase in data resulted in only a 3x increase in task performance times. Relative comparisons between designs were consistent across display sizes based on time and accuracy. However, task workload and user preference suggested that graphical encoding differences were more important on a smaller display with less data, while spatial grouping became more important on a larger display with more data. This suggests that some visualization designs are more perceptually scalable than others.

Based on these results it does not appear that visual acuity is a limiting factor for information visualization. However, that work did not specifically test the effect of visual acuity. It is possible that scaling up visualizations may be more efficient with display sizes up to the point of visual acuity than with display sizes beyond the point of visual acuity.

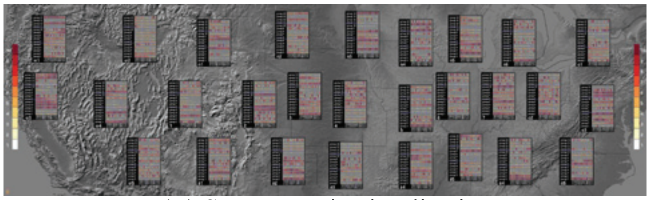
This work directly expands on the previous work by considering three different display size conditions (within, equal to, and beyond visual acuity) to specifically test the influence of using a display that exceeds visual acuity. We also increased the maximum size dataset 19x, from 5,000 to 94,000 data points. Eccentricity effects would be more likely to result in performance degradation with the larger dataset sizes. Additional information was added by decreasing the size of individual graphical elements to 2 pixels in width. The smaller graphical elements allowed us to ensure that users could not see all data when standing in any single location. They were forced to physically move to see the entire visualization.

VISUALIZATION DESIGNS FOR LARGE DISPLAYS

Before conducting the study we first had to design the visualizations for the large display. We were interested in visualizing datasets with a combination of spatial, temporal,



(A) Attribute-centric visualization



(B) Space-centric visualization

Figure 2. Visualization designs.

and multidimensional data because of their prevalence in many application areas as diverse as sociology, epidemiology, and bioinformatics. The exact data used was artificially generated and consisted of spatial (U.S. states), multidimensional (multiple demographics groups), and temporal (multiple years) data.

The two visualization design strategies we chose were termed attribute-centric and space-centric (Figure 2). Choosing two opposing visualizations allowed us to compare the perceptual scalability of different designs. In general there is a tradeoff between scanning multiple simple views versus the complexity of a single view [14, 30].

The attribute-centric design had a separate small map for each year/group combination. This design is similar to Tufte's concept of small multiples [26] and Visualization Spreadsheets [8]. The space-centric design consisted of a single large map with embedded visualization overlaid at each location. This design is representative of single complex views like those generated by ViA [13]. An individual small map and an individual embedded visualization can be seen in Figure 3. In order to prevent the effect of previous knowledge, we used only group numbers instead of meaningful attribute names and abbreviated state labels according to their region. For example, West state labels included w1 and w2. Each individual bar was 2 pixels wide and between 0 and 10 pixels high. A continuous color scale corresponding to the bar height was used as a redundant encoding.

In the previous experiment [31] we saw that the spatial grouping with the space-centric visualization scaled better. In this experiment we set the amount of data in the smallest display condition equal to the amount of data in the previous experiment's largest display condition. This allowed us to determine if the advantage was due to the size of the display or the amount of data.

Graphically Scalable Encodings

When designing visualizations for large displays it is helpful to distinguish between encodings that are and are

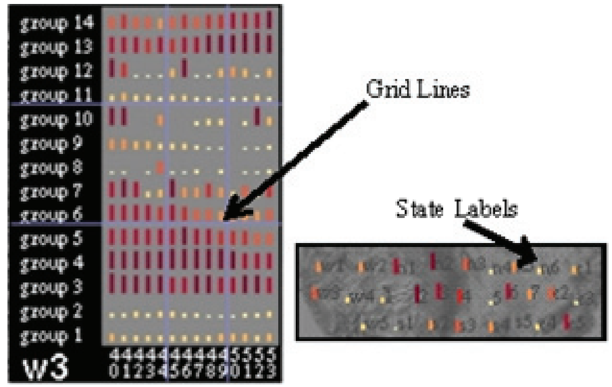


Figure 3. Physically adaptive visualizations.

not graphically scalable. A graphically scalable encoding can be scaled simply using additional pixels. In the previous experiment time-series graphs were used as one case of embedded visualizations. These used colored lines to represent different categorical groups. Because color is not a graphically scalable encoding (adding more pixels does not allow us to distinguish more colors), this visualization design was no longer usable when we wanted to scale up the number of categories. On the other hand, the number of spatial locations was scalable.

Color can still be a useful encoding on larger displays if the number of colors required is held constant, despite the lack of color receptors in peripheral vision. In a pilot study, bars with colors were preferred to bar heights alone because distant colors were easier to compare than distant sizes. In general, characteristics of the display should be considered when choosing graphical encodings [20].

Physically Adaptive Visualizations

The physical size of the display coupled with the lack of virtual interaction created certain design considerations for physically navigating the visualizations. The most simplistic of these considerations was that labels needed to be placed at multiple strategic locations. For the attribute-centric visualization this meant placing group labels at both the left and right sides of the display. While we could have also placed them in the middle, we felt this would create a meaningless grouping and interfere with overview tasks.

We also used what we have termed physically adaptive visualizations. Physically adaptive visualizations create the visual illusion that some details disappear as the user moves away from the display. If carefully designed, visualizations can be created for large, high resolution displays that more fully take advantage of visual aggregation and human perceptual abilities. By using light colors that blend with the background, users have access to details when close without being overwhelmed by details when standing back to get an overview (Figure 3). In the space-centric visualization we used light blue gridlines that could only be seen when users were close enough to make use of them. Likewise, in the attribute-centric visualization we used light gray state labels that could only be seen when close to the display. If we had simply made these labels black they would have quickly overwhelmed the visualizations. This approach is likely to work better with wider displays than with taller displays where the highest pixels cannot be accessed by walking.

Another result of physical navigation was visual aggregation. The proximity of bars in the space-centric visualization resulted in visual aggregation. This meant that although individual bars were not distinguishable from a distance, general patterns emerged.

EXPERIMENT

The main goal of this study was to explore the effects of using displays that exceed the limits of visual acuity for scaling up information visualizations. In general, we wanted to know *how scaling up visualizations using a display with a resolution exceeding visual acuity would affect user performance*. As a secondary issue we wanted to confirm that the selected visualization designs were still perceptually scalable with significantly more data.

Participants

Eighteen volunteers (14 male, 4 female) participated in this study. Most were computer science students at a large public university recruited from HCI related classes.

Equipment

An 8x3 tiled display of LCD monitors was used (Figure 1). Each monitor was a 17 inch LCD with a resolution of 1280x1024 (~96DPI) and a dot pitch of 0.264mm. The total resolution of the display was 10,240x3,072 (approximately 32 Mp) and was 9 feet wide by 3.5 feet high. The bottom of the display was 36.75 inches off the floor. A wider display allows users to access pixels by walking. We avoided issues with the gaps between tiled monitors by ensuring that information never straddled monitor boundaries.

Design

We used a 3x2x9 design with the following independent variables: display size (small, medium, large corresponding to within, equal to, and beyond visual acuity - data density was constant), visualization design (space-centric, attribute-centric), and task (3 detail, 4 overview, and 2 complex). The visualizations were described in the Visualization Designs for Large Displays section. Display size was a between subjects variable while visualization and task were within subject variables. Task completion time, accuracy, subjective workload, and user preference were recorded.

Display Size and Visual Acuity

Various interdependent perceptual factors are at play when using large displays. Eye and head movements are used to bring objects into foveal vision. The effect of these movements on the distance and viewing angle parameters are relatively minor compared to the effect of walking. When walking is required to bring objects into foveal vision then the distance from and viewing angle for other objects changes more dramatically. The field of view also increases or decreases based on a user's physical distance from the display.

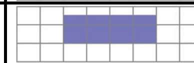
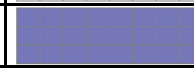
Display Size	Data		Display	
	Groups x Years	Data Points	Pixels	Area
Small	14 x 14	5,488	2560x768	
Medium	29 x 29	23,548	5120x1536	
Large	58 x58	94,192	10240x3072	

Table 1. Display size conditions.

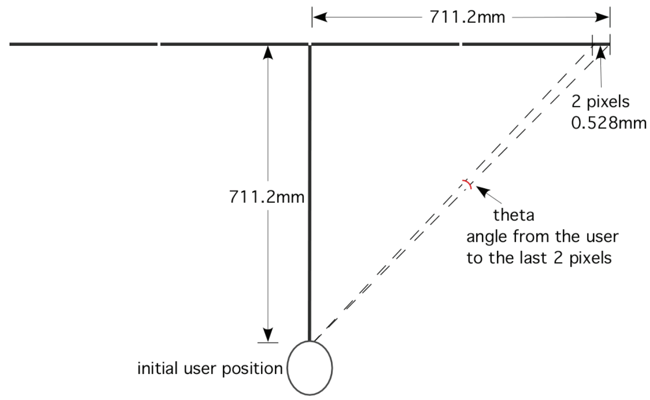


Figure 4. Medium display condition (equal visual acuity)

By *visual acuity* we mean the definition commonly used when referring to 20/20 vision -the ability to distinguish two points (point acuity) [27]. This definition is based on both distance from and the size of a target. Those two parameters along with the viewing angle are then used to calculate the visual angle subtended by a target. For a fixed target size this means that targets that are either too far away or viewed from too great a viewing angle will be "beyond visual acuity" because the visual angle subtended will be too small (< 1 minute of arc, 1/60 degree). In the large display condition, there was no spot where everything could be distinguished with only eye and head movements because either the distance or the viewing angle would be too great. For example, if users stepped back for an overview, they would not be able to see individual elements. If they stepped forward for a detailed view, they could see a small region of elements, but not the elements on the far side of the display.

Specifications for each display size are shown in Table 1. The aspect ratio was kept constant across display sizes by only using part of the display height for the small and medium display conditions. The display size condition that was roughly equal to visual acuity (medium size) is shown in Figure 4. In the medium display condition the user started at 711.2 mm (90 degree field of view/half the width of the illuminated surface) away from the center of the display. The starting distance was not the same for all three display size conditions.

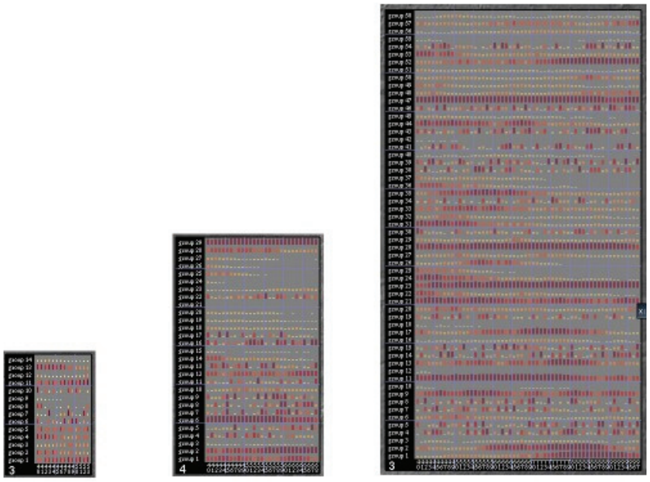


Figure 5. Space-centric design on different displays.

For the medium condition the angle from the user to the last 2 pixels, which was the size of visual elements, was 0.0212 degrees (1.272/60). This is slightly bigger than visual acuity (1/60 = 0.0166 degree). This was to compensate for the fact that the last two pixels were viewed at an angle and may be harder to see. As the user moved closer, the angle was too great to see the outermost pixels. As a user moved farther away, the pixels became too small to distinguish.

The data density and size of individual graphical elements were kept constant across display sizes, while the amount of data increased proportionally with display size (Figure 5).

Tasks

The tasks are described in Table 2. An artificial dataset was generated consisting of 58 time points and 58 attributes for 28 states. This choice of data was modeled after typical demographics datasets available from sources such as the Census Bureau. Data generation provided for an additional level of experimental control.

The datasets had to be created carefully as to result in a fair comparison. Detail task datasets for different types were generated similarly; there was a single definite highest value that was different from the next highest value by either 2 or 4 pixels. For OG tasks, at least 60% of the values were within the specified range. Generation of OT datasets was a little more complex; 4/28 states did not match the pattern and for the remaining 24 states 80% of the groups matched the pattern. Up then down (or down then up): states matching the pattern were split into 4 groups with different inflection points. For OST tasks, states in the fastest increasing area had initial values between 4.5 and 6.5 and increased by a number between -0.3 and 1.2 each year, whereas the rest of the state values changed by only one pixel. For OS tasks, states in the highest area had values between 7 and 10, with some noise added. A correlation was created between two of the groups for CG tasks. An increase/decrease in one group caused an increase/decrease in another group. For CS tasks, matching states were exactly the same, but participants were not told.

Group	Type
Detail	**DG**: Find a group, given a year and location **DT**: Find a year, given a group and location **DS**: Find a location, given a group and year
Overview	**OG**: Populations are in the range [<4,4-7,>7] **OT**: Population have gone [up,up/down, down/up, down] **OS**: Populations are highest in [N, S, W, E] **OST**:Populations increase fastest in [N,S,W,E]
Complex	**CG**: Cause/effect relationship **CS**: Find a location that is similar to a given location

Table 2. Tasks (D: detail, O: overview, and C: complex; G: group, T: time, and S: space).

Procedure

Participants were assigned to a display size condition based on their self reported familiarity with computers, large displays, information visualization, and geographic information systems. The groups were kept as even as possible in terms of these factors. The average familiarity ratings for each group can be seen in Table 3. None of the differences between groups was statistically significantly. The eye sight of participants was not tested and they were only asked if they had corrected vision. We assumed that participants had approximately 20/20 vision and considered that to be a reasonable assumption for the sake of generalizing the results to the overall population.

Participants stood and started at a viewing distance equal to half the width of the illuminated surface (different for each display size). This meant each participant started with a 90 degree field of view. A mark was placed on the floor where users were asked to stand when they started a task. After beginning the task, users were free to move about.

The participants went through a training session to get familiar with the visualizations before beginning. Because visualization was a within subjects factor, half of the participants in each condition used the space-centric first. Before each type of detail task they did a practice task. Each type of task was then performed twice with a given visualization. This meant that each participant performed 2 (visualizations) x 9 (task types) x 2 (trials) = 36 experimental tasks.

Display Size (visual acuity)	Computer	Large Display	Information Visualization	Geographic Information Systems
Small	4.8	3.5	2.7	2.0
Medium	5.0	3.3	3.2	3.3
Beyond	5.0	3.2	2.8	3.0

Table 3. User familiarity ratings (1=strongly disagreed, 5=strongly agreed).

After each group of tasks (DG and DT, DS, Overview, CG, and CS) participants answered five questions which were a modified version of the NASA Task Load Index. The questions asked the participants to rate the level of mental demand, physical demand, effort, perceived performance, and frustration on a scale from 0 to 10. At the end of the experiment they filled out a post-hoc questionnaire indicating their visualization preference for each task.

RESULTS

Time and accuracy averages can be found in Tables 4 and 5. Time, accuracy, and workload data was first analyzed using a three-way mixed model ANOVA with display as a between subjects factor and visualization and task as within subjects factors. Post-hoc two-way ANOVAs were then done for each task and significant factors were further compared using Tukey's HSD. Because task had such a strong influence, we only report the results by task rather than presenting overall results.

Increase Factor for Time

The increases in time between the small and medium, and the medium and large display conditions are shown in Figure 6. This is a comparison between how quickly time is increasing as the display gets larger. The display size (and amount of data) increased by a factor of four between conditions (small x 4 = medium, medium x 4 = large). As the display got larger, almost every task (DG, DS, OT, OS, OST) resulted in a less than proportional increase in time (<4x). The OG and CG tasks were the only tasks where users were less efficient in terms of time as the display got larger (medium/small < large/medium).

Task	Attribute-Centric			Space-Centric		
	Small	Medium	Large	Small	Medium	Large
DG	10.98	28.75	56.73	7.68	14.43	21.25
DT	15.73	39.53	81.04	8.29	8.48	14.88
DS	6.15	8.74	9.76	44.69	63.68	81.60
OG	6.10	11.24	27.54	9.07	10.15	20.00
OT	25.20	40.48	57.04	27.22	27.87	26.61
OS	10.84	28.75	67.48	3.59	15.37	19.21
OST	22.95	31.21	40.81	26.42	22.93	12.70
CG	52.78	55.16	73.92	60.68	69.68	166.50
CS	52.71	56.34	61.14	29.57	46.75	74.83

Table 4. Average task completion times (in seconds).

Task	Attribute-Centric			Space-Centric		
	Small	Medium	Large	Small	Medium	Large
DG	100.0	91.7	75.0	91.7	91.7	100.0
DT	91.7	91.7	91.7	83.3	100.0	91.7
DS	91.7	100.0	91.7	91.7	100.0	100.0
OG	100.0	83.3	83.3	100.0	83.3	75.0
OT	0.0	66.7	58.3	33.3	75.0	100.0
OS	100.0	83.3	100.0	100.0	100.0	100.0
OST	83.3	100.0	91.7	75.0	100.0	100.0
CG	16.7	83.3	58.3	25.0	83.3	33.3
CS	58.3	75.0	91.7	83.3	91.7	83.3

Table 5. Accuracy (percent correct).

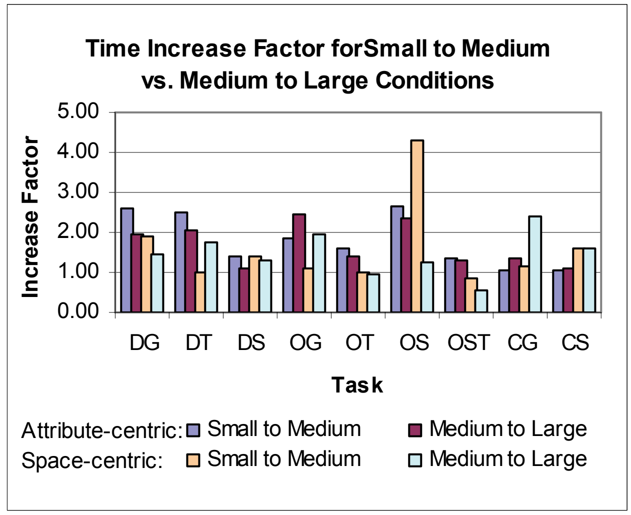


Figure 6. Factor increases in task completion times

Detail Tasks

The DG (given 1 year, comparing groups) and DT (given 1 group, comparing years) tasks were similar because the number of groups and years increased with display size. We normalized the task completion times for these tasks by dividing the actual task completions times by the number of groups (14, 29, or 58). The DS task required finding a location with the highest value when given a group and a year. Because the number of locations was fixed, the data for this task was not normalized.

DG and DT Tasks

Overall the space-centric visualization resulted in better user performance than the attribute-centric visualization for the DG and DT tasks. It was significantly faster (DG task: $F(1,15)=30.46$, $p<0.01$; DT task: $F(1,15)=67.44$, $p<0.01$), physical workload was lower (3.11 vs. 5.33, $p<0.01$), perceived performance was better (8.53 vs. 7.6, $p=0.043$), and frustration was less (1.56 vs. 3.39, $p<0.01$). Users also preferred the space-centric visualization for these tasks (DG task: small-3/6, medium-4/6, large-5/6; DT task: small-5/6, medium-5/6, large-5/6). There were no significant differences in terms of accuracy.

The only significant difference related to the display size was that the space-centric visualization was less mentally demanding than the attribute-centric visualization (2.83 vs. 7.08, $p<0.01$) in the large display condition.

DS Task

The attribute-centric visualization resulted in better user performance than space-centric for this task – opposite of the DG and DT tasks. Users were significantly faster with the attribute-centric visualization (significant display size x visualization interaction $F(2,15)=8.59$, $p<0.01$, main effect by visualization $p<0.01$, main effect by size $p<0.01$, faster

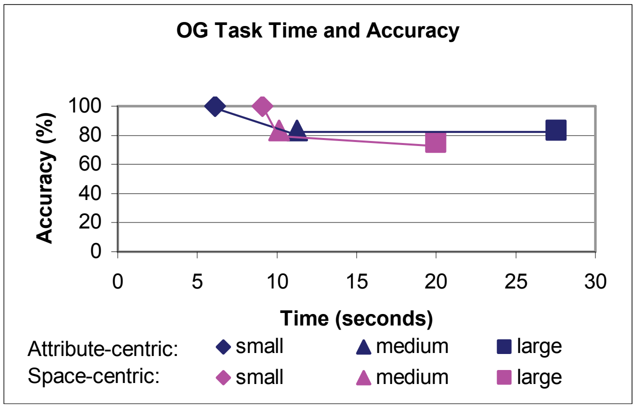


Figure 7. Speed and accuracy for the OG task. Small is significantly faster than large and significantly more accurate than both medium and large.

for every display size p<0.01). The attribute-centric visualization also resulted in significantly less mental workload (1.94 vs. 6.54), less physical workload (1.89 vs. 5.89), less effort (1.54 vs. 6.43), better perceived performance (9.39 vs. 7.80), and less frustration (1 vs. 2.8) than space-centric (all p<0.01), and users always preferred it (small: 5/6, medium: 4/6, large: 5/6). There were no significant differences in terms of accuracy.

In terms of display size, the only significant difference was not surprising; The space-centric visualization was significantly faster in the small display condition (44.69s vs 81.6s) compared to the large display condition (p<0.01).

Overview Tasks

OG Task

The OG task required participants to see the general range of values. The visualizations were significantly different only in the large display condition where the space-centric visualization was significant faster than the attribute-centric visualization (20s vs. 27.54s, p=0.05). User preference was nearly equally split between the two visualizations (small:2/6, medium: 3/6, large: 3/6 preferred space-centric).

Increasing the display size seemed to have a negative effect on user performance for this task (Figure 7). Not only were the small and medium sizes faster than the large (display x visualization interaction F(2,15)=7.09, p<0.01, main effect by display size F(2,15)=11.45, p<0.01, small vs. large and medium vs. large p<0.01), but time increased faster between the medium and large displays than between the small and medium displays (1.12x to 1.97x, attribute-centric: 1.84x to 2.45x). The small display condition (100%) was also significantly more accurate (main effect by size F(2,15)=4.2, p=0.036) than both the medium (83.3%, p=0.01) and large conditions (79.17%, p=0.022).

OT Task

The OT task required the user to find a temporal trend. The space-centric visualization resulted in better user performance than the attribute-centric visualization for this

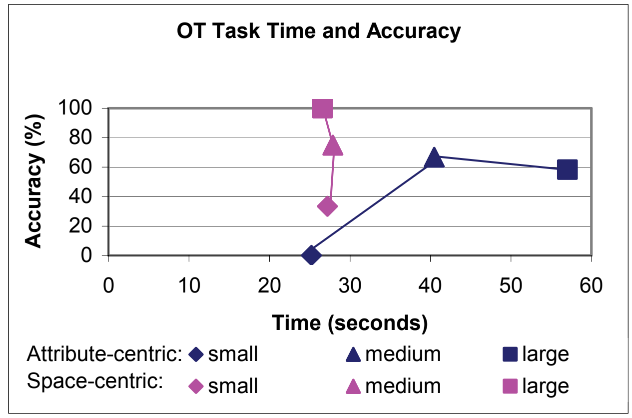


Figure 8. Speed and accuracy for the OT task. Accuracy was significantly better with medium and large than small. Space-centric was significantly faster than attribute-centric in the large condition.

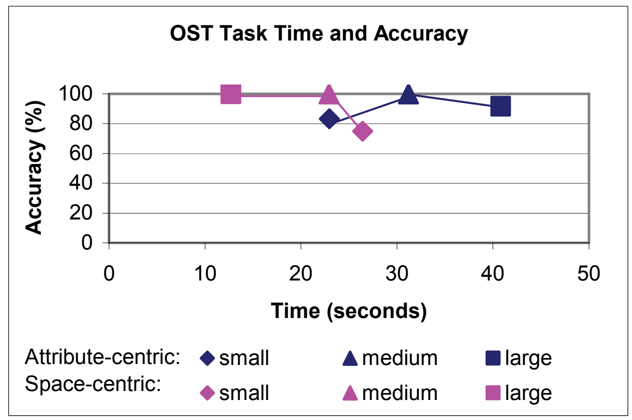


Figure 9. Speed and accuracy for the OST task. Medium is more accurate than small.

task (Figure 8). The space-centric visualization was significantly faster in the large display condition (display x visualization interaction F(2,15)=3.91, p=0.043, main effect by visualization F(1,15)=8.31, p=0.011, large – visualization comparison p=0.0247), and significantly more accurate overall (main effect by visualization F(1,15)=5.56, p=0.032). Users also preferred the space-centric visualization for this task (small:5/6,medium:6/6, large:5/6).

In terms of display size, both the medium (70.83%) and large (79.17%) sizes were significantly more accurate than the small display condition (16.67%, p<0.001).

OS Task

The OS task required participants to find a spatial trend in the data. The space-centric visualization was better than the attribute-centric visualization for this task. It was significantly faster in every display condition (visualization x display interaction F(2,15)=3.91, p=0.043, visualization main effect F(1,15)=8.31, p=0.01, comparison was p<0.01).

Not surprisingly, the small condition was significantly faster than the large condition for both visualizations, and the medium condition was faster than the large condition for the space-centric visualization.

OST Task

The OST task was about finding a spatiotemporal pattern. The space-centric visualization appears to be preferable for this task. It resulted in a non-significant decrease in task completion times on the larger displays (Figure 9), and was preferred over the attribute-centric visualization (small: 5/6, medium: 6/6, large: 5/6).

In terms of display size, the medium display (100%) was significantly more accurate than the small display (79.2%, main effect by size $F(2,15)=4.77$, $p=0.025$, $p=0.022$).

Workload

Workload measurements were recorded for all overview tasks combined. Overall, the space-centric visualization was better than the attribute-centric visualization for overview tasks. It resulted in less mental demand ($F(1,15)=10.17$, $p<0.01$, 5.18 vs. 7.11, $p<0.01$)) and less effort ($F(1,15)=8.9$, $p<0.01$, 4.94 vs. 6.78, $p<0.01$).

In the large display condition the space-centric visualization resulted in less physical demand than the attribute-centric visualization ($F(2,15)=6.64$, $p<0.01$, $p<0.01$). Performance was also perceived to be better ($F(2,15)=4.64$, $p=0.048$) with the space-centric visualization in the medium ($p=0.011$) and large conditions ($p=0.026$).

Complex Tasks

The complex tasks were harder than any of the other tasks because they required complex pattern matching between states or finding correlations between groups across time.

CG Task

The CG task required finding a cause/effect relationship. The attribute-centric visualization was significantly faster than the space-centric visualization (visualization main effect $F(1,15)=7.26$, $p=0.017$). Despite attribute-centric being faster and more accurate, in every display condition 4 of 6 users preferred the space-centric visualization.

In terms of display size, showing more data using the medium size display improved performance, but performance dropped-off with the large display (Figure 10). Even though the small and medium displays were significantly faster than the large display (display size main effect $F(2,15)=4.03$, $p=0.04$, both $p<0.01$), this was the only task, in addition to OG, where time increased faster from medium to large than from small to medium. The medium display condition was significantly more accurate than both large and small (size main effect $F(2,15)=7.5$, $p<0.01$, medium vs. large $p=0.012$, medium vs. small $p<0.01$).

CS Task

The CS task was a pattern matching task. There were no significant time or accuracy differences for this task. The only significant workload measurement for the CS task was for frustration. The space-centric visualization was less frustrating than the attribute-centric visualization overall (visualization main effect $F(1,15)=5.5$, $p=0.033$, 2.1 vs.

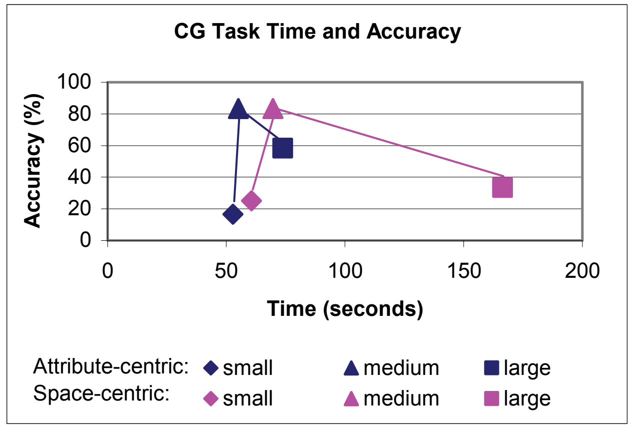


Figure 10. Speed and accuracy for the CG task. Small and medium were significantly faster than large, and medium was the most accurate display size.

3.36) and particularly when using the small display (interaction $F(2,15)=6.03$, $p=0.012$, comparison $p=0.028$). Most users preferred the space-centric visualization for this task (small: 5/6, medium: 3/3, large: 4/6).

For the attribute-centric visualization the large display was significantly less frustrating than the small display ($p<0.01$).

Summary of Results

Detail Tasks

The results from the detail tasks suggest that using a display beyond visual acuity has very little influence on these tasks. There were no significant differences in accuracy or normalized completion times for the DG or DT tasks between display sizes. The space-centric visualization was ideally suited for the DG and DT tasks while the attribute-centric visualization was ideally suited the DS task.

Overview Tasks

Results from the overview tasks suggest that the effect of using a display that exceeds visual acuity depends on the task. The additional data that could be visualized using the larger display resulted in improved accuracy for the overview tasks involving time and space. On the other hand, for the OG task, there was a decrease in accuracy with the larger display. The space-centric design was particularly good for overview tasks on the large display.

Complex Tasks

The complex task results revealed a situation where the attribute-centric visualization resulted in better user performance. The CG task, which required finding the strongest correlation, resulted in faster task completion times with the attribute-centric visualization than with the space-centric visualization. Despite this, users still preferred the space-centric visualization.

DISCUSSION

The main goal of this study was to explore visual acuity as a factor in the perceptual scalability of information visualizations for large, high resolution displays. We wanted to know what would happen to user performance as the data was increased using a display with enough pixels that physical navigation was required to see everything. The results suggest that for some tasks performance can actually become more efficient and accurate when showing more data using larger displays. This is supported by the findings that almost all tasks resulted in less than proportional time increases and using the large display resulted in accuracy increases as much as 20% for temporal pattern tasks. These results agree with the previous study [31] in suggesting that visualizations can be perceptually scalable. It adds to that study by showing that this still holds with a larger dataset, when 19x more data is packed on the same size display.

A secondary aim for this study was to confirm the perceptual scalability of the visualizations. As in our previous work, we found that in general the space-centric visualization resulted in better user performance than the attribute-centric visualization. This was particularly true in the largest display condition. In three of four overview tasks the attribute-centric visualization was faster than the space-centric visualization in the small display condition, but in the medium and large display conditions the space-centric design was faster. The task also played a role in this scaling with the advantages of the space-centric being most evident on spatial and temporal overview tasks.

Overall, the role of visual acuity seemed to be outweighed by the advantages of additional data. In five out of nine tasks time increased faster between the smaller displays than between the larger display sizes. In general users were actually becoming more efficient using the additional data, despite the physical navigation that was required.

One might wonder why the space-centric visualization has an advantage. Recall that there was the same amount of data in the small display condition as in the large display condition from the previous experiment. Although the amount of data was the same, the advantages only became apparent on the large display. This suggests that the advantages of the space-centric visualization were more related to the display size than the amount of data. Therefore space-centric designs seem to be even more useful on large displays than they are on smaller displays, regardless of the amount of data.

Spatially grouping information and visual aggregation are both important factors in the performance of space-centric visualizations on large displays. Visual aggregation resulted in less physical navigation and thereby allowed for less mental demand and effort. Another observation is related to information overload. Throughout the experiment, some participants stated that it felt like a lot more data was being shown with the attribute-centric visualization (when in fact data was equal). Although performance was better with the attribute-centric visualization on the CG task, more users preferred the space-centric visualization for this task. This may be because they were less intimidated by the space-centric visualization.

In addition to the results of this study we also discussed information visualization design issues when physically navigating a display. By using physically adaptive visualizations users can see details when close to the display without the visualization being overwhelmed by grids and labels when the users are far away. Graphically scalable encodings should also be used. These techniques can be applied in areas beyond visualization for large display interfaces.

All of these factors support the need for additional research into visualizations that are specifically designed for large, high resolution displays. If visualizations are created that consider the display during the design phase then users can take advantage of the additional data that can be displayed on large, high resolution displays despite having to physically navigate to access all of the information. These results provide some insight into designing visualizations that scale up for large displays.

CONCLUSION

The scalability of information visualizations has typically been limited by the number of available display pixels. This work explored the effect of using large, high resolution displays to scale up information visualizations beyond potential visual acuity limitations. Results showed that performance on most tasks was more efficient and sometimes more accurate because of the additional data that could be displayed, despite the physical navigation that was required. Hence, visualization is not limited by visual acuity. This offers new opportunities for scaling up visualizations to very large datasets. Visualization design guidelines were also discussed.

Future work includes comparing visual aggregation to computational aggregation to determine the tradeoffs that exist and exploring the scalability of information visualization specific interactions such as brushing and linking when using large, high resolution displays.

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