Performance Evaluation of Navigation Approaches on High-resolution Displays

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ABSTRACT

We conducted a study to discover if the data navigation techniques suitable for high-resolution displays differed significantly from those traditionally used for single-screen desktop displays. The high-resolution capability of the former display makes it possible to show more data at once without having the user drill-down to get to the details. At the same time, the larger physical size makes it difficult for the user to interact with such a display using current day interaction techniques. Given these factors, we compare the performance of users on tasks that involve navigating into hierarchically-structured data. The specific visualization we use is a cushion treemap, displayed at multiple resolutions—on a 3x3, 17" tiled screen display; on a 2x2, 17" tiled screen display; on a single 17" screen display, and on a 66" SMART Board™. Through the performance evaluation of 24 users, we show that beyond a certain resolution and physical screen size, the drill-down technique fares relatively poorly, while the straightforward technique of displaying all the data at once results in better performance at the tasks we studied.

Author Keywords

High-resolution displays, large screen, navigation strategies, performance testing, Fitt's law.

ACM Classification Keywords

H1.2. Models and principles: Human factors; H5.2. Information interfaces and presentation: User interfaces.

INTRODUCTION

One of the current problems in data visualization is that display size places a limit on how much data can comfortably be shown at one time, without a significant cognitive load on the end user. The displays in common use today are just too small to show the overview and the details together for large datasets: the entire amount of available information cannot be presented in a useful fashion at once or with equal focus. With the advent of large-size high-resolution displays, it has now become technically and economically feasible to present more data than on an analogous smaller-size display. As an exciting new area of research, large screens have the potential to change how people interact with computers: users would no longer need to zoom and pan to focus on segments of interest within their dataset. Instead, the data would simply be available for them to view without further interaction required.

The goal of our study is to analyze user performance given a hierarchically-structured dataset using two navigation strategies on four display configurations. We plan to determine whether the effectiveness of these two navigation techniques is dependent on physical screen size, resolution, or both. Similarly, we make a recommendation as to which navigation approach is more effective for a given configuration.

BACKGROUND AND RELATED WORK

The realm of computer displays has been steadily progressing from yesteryear's small monochrome monitors to today's desktop displays that have resolutions as high as 1600x1200 pixels with millions of colors. Increasingly, we also see the emergence of large-size displays (40" or higher) with resolutions better than ever before. With the increasing need of screen space for display and organization purposes, the use of multiple monitors at the workplace has flourished. These new devices also open up new perspectives in the field of immersive environments such as Virginia Tech's CAVE [4], as their high resolution can be leveraged to offer unique ways to visualize data.

Screen Size Does Matter

Not only do large displays have the power to change the way data is presented, perceived, and analyzed, but they also impact the social workplace. In fact, research work has been conducted using large screens placed behind desks as an alternative to desks overcrowded with multiple monitors [5]. A larger display placed further away from the human eye is equivalent to the original setup in terms of visual angle, since the image formed on the retina is the same size in both cases [20]. Beyond a single-user scenario, whenever the concept of collaborative work practices arises, large screens once again prove to be an ideal solution [9, 12, 21], as they support attention gathering from a larger audience. They are easy for collaborators to see and interact with. Dudfield *et al.* studied large displays in terms of the human factors issues involved. Their subjects were military command teams using large displays for viewing tactical information and the subjective response was clear: "You can't do without it" [8]. Consequently, researchers have increasingly pursued their inclusion in the design of futuristic workspaces [6, 9, 13, 18, 21].

In addition, large screens seem to greatly impact users' attention [14] and are so immersive that they are now being seen as an alternative to head-mounted displays for virtual environments [11].

The use of large screens clearly show benefits compared to standard-size desktop monitors. However, the benefits of interaction techniques traditionally associated with smaller displays may not hold as the screen real estate increases.

Navigation Strategies

Because of screen-space limitations with traditional desktop displays, various navigation strategies have been developed to present the available data to the users in a more manageable form. Based on Shneiderman's mantra for visualization techniques: "overview first, zoom and filter, then details on demand" [16], most of these approaches require the user to first select an area of focus before indicating (via suitable interaction with the interface) that further details are requested. This action brings details about the selected focus area to the foreground, replacing the overview that was initially occupying the same screen space. This approach has generally been described as the *drill-down* navigation strategy for viewing datasets that would require a much larger display area than the available screen space to be seen entirely.

As opposed to the drill-down strategy, another approach generally used when the dataset can fit onto the available display space, is referred to as the *details-all-the-time* approach to data navigation. In this case, the dataset can be seen and analyzed in its entirety without having the user initiating any physical interaction to observe even the lowest level of details. However, a possible drawback of using such an approach on large displays is that because of their immersive nature, perceiving comprehensible data in one's whole field of view might result in a high cognitive load.

Prior Performance Studies with Large Displays

Given that monitors are available in various sizes, Simmons [17] evaluated user performance on a number of usual office tasks based on monitor size, with 15", 17", 19", and 21" cathode ray tube monitors. After running the experiments on 50 participants, Simmons concluded that the usage of a 21" monitor resulted in much better performance as opposed to the other three display sizes. Similarly, through another independent study, Czerwinski *et al.* [7] conclusively report that there is a significant increase in performance speed when using a larger screen compared to a 15" screen.

Swaminathan and Sato built a grid of multiple screens to study how methods of interaction vary with the size of displays: they discovered via the design of their system, Prairie, that "when a display exceeds a certain size, it becomes qualitatively different" [19]. They also state that they earlier considered a large display like a traditional display, merely larger. But they later concluded that this assumption was entirely false. Large displays necessitate a different outlook in terms of the interaction techniques used with them.

The Potential of High Resolution

Screen resolution refers to the total number of pixels available on the screen for display. The dots per inch (DPI) measure refers to pixel density and is screen-size dependent. For example, a 17" display at 640x480 pixels resolution has a much higher DPI (typically 96 DPI) than a wall-sized display with the same 640x480 pixels resolution [23].

To study the effect of combining high resolution with the large size of a display, Baudisch *et al.* incorporated a liquid crystal display (LCD) screen into a display created from a projected low-resolution image, effectively wrapping a small high-resolution area inside a larger low-resolution area. A detailed view of the entire image would not be available at once. Rather, details for a certain area could be viewed by panning in order to bring it under the LCD portion of the display. Baudisch *et al.* demonstrated that people performed faster at tasks with this hybrid display because there was no need to zoom to view the data [1]. However, in his experiment, the objects in the periphery were displayed at lower resolution than these closer to the focus of attention. As the introduction of high-resolution displays impacts user performance positively, it might be advantageous to provide a large display entirely composed of high-resolution displays.

The Treemap Visualization Technique

First described by Shneiderman as an alternative to conventional tree representation techniques, where parent and child nodes are displayed as nodes of a tree, treemaps are a space-filling technique for visualizing large hierarchical datasets, based on recursive subdivision of a rectangular image space. The original motivation for this work was to gain a better representation of the utilization of storage space on a hard disk as viewed from the perspective of a multiple level directory of subdirectories and files [10, 2]. Cushion treemaps are a type of treemap where shading of squarified blocks is used instead of lines to demarcate blocks representing data nodes [22]. Compared to traditional treemaps, cushion treemaps are better at utilizing pixels. As "a pixel is a terrible thing to waste" [15], shading the blocks avoids the need to draw borders between them, thus increasing scalability.

EVALUATION TOOL

In order to compare performance on navigation tasks, we developed an evaluation tool to implement the cushion treemap technique for hierarchical data. Treemaps allow us to easily control the data density for our experiment by choosing the right size of dataset to be visualized.

Various implementations of treemaps are available for use, but unfortunately, none of them supported all the features we needed. To compare and contrast between drill-down and details-all-the-time navigation strategies, we needed the flexibility to select the number of levels shown on the initial treemap display. Consequently, in our treemap implementation, the cushions shown on screen are summaries of the contained sub-trees. In fact, the content of the current cushion only becomes visible upon mouse clicking as it expands to fill the entire screen, replacing the root-level tree. Deeper nodes become available only after their immediate parent has been expanded into view. In addition, other needed features included control over showing or hiding captions and tool tips so that they could be selectively enabled or disabled for either approach that we wanted to test.

We built upon an open-source implementation of the cushion treemap made available by Bouthier [3] that we customized to suit our need. Specifically, we added support for showing one-level overviews of the underlying tree data: selecting the “Details on Demand” approach hides all but one level of the data. In case of showing details-all-the-time, it is important for users to be able to identify intermediate nodes in the tree, without having to know about the leaf nodes. To accommodate this, we added captions at intermediate levels of data. These captions were semi-transparent while the font size was level-dependent: the captions for higher levels were larger and more transparent compared to those for lower levels that were smaller and darker, enabling them to be seen even behind the larger ones. Upon completion of our implementation effort, with the configuration panel for the actual tool, we could quickly control the parameters for each step of our experimentation (Figure 1).

EXPERIMENT DESIGN

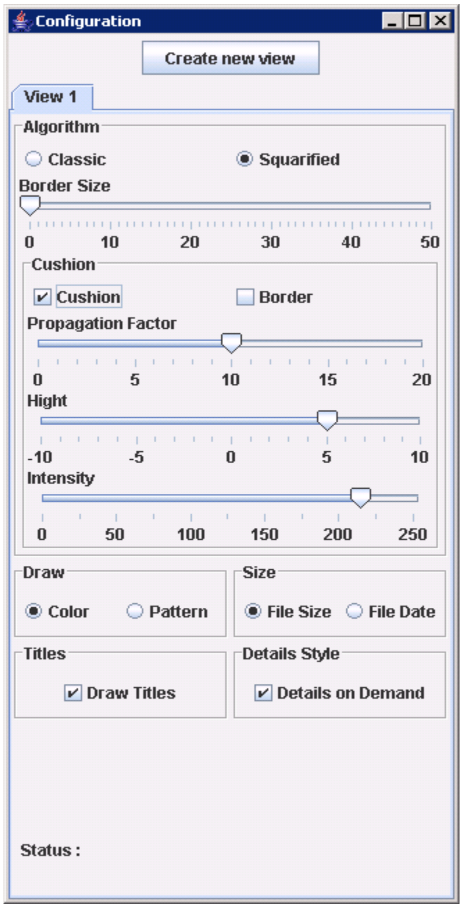
The high-resolution capability of the large display makes it possible to show more data at once, rather than have the user be forced to drill-down to get to the details, compared to the traditional details-on-demand paradigm. At the same time, the larger physical size makes it difficult for the user to interact with such a display using current day interaction techniques.

In our study, we analyze whether for a fixed dataset, it is better performance-wise to suit a display size to entirely and comprehensively display the data while potentially increasing the cognitive load, or to keep a fixed screen size while forcing a user to drill-down to get to the details.

In addition, to discover whether the data navigation techniques suitable for high-resolution large displays differed significantly from those traditionally used for a single high-resolution desktop display, we tested twenty-four users. The participants were college students, from a wide variety of academic backgrounds. Because of the physical size and setup of our display configuration, we ensured that they were all of average height as well as being intermediate to experienced computer users.

Hierarchical File Organization

We considered various data that we could use for such an evaluation. A regular geographical map was a potential candidate, but it would mean that users familiar with a particular region or with geography in general would have an advantage over others, and thus bias our experiment.



○ Classic ● Squarified

☑ Cushion ☐ Border

● Color ○ Pattern

● File Size ○ File Date

☑ Draw Titles

☑ Details on Demand

Figure 1. The configuration panel

Although the most common usage of treemaps is to visualize directory trees, we realized that tasks based on such an approach would necessitate that the user have prior knowledge about the directory structure. Since that alternative might also potentially skew our results, we opted for data that would be independent of prior knowledge, yet be structured hierarchically.

We finally decided to use random words and structured them hierarchically. We created a 4-byte file for each word, so each would occupy the same number of pixels on screen, ensuring a homogeneous data distribution throughout the display. We chose words at random from an English dictionary. Words were arranged into directories according to the first n characters of which they are composed. In order to keep the depth of this directory manageable, we restricted it to four levels. For example, the word “abstract” was placed in a path “a/ab/abs/abstract.” Similarly, the word “psalmist” would be placed in “p/ps/psa/psalmist”, while all words starting from “dis” would be placed in the same directory, regardless of the fourth letter of the word (Figure 2). Finally, given our limited screen real estate, we experimented and selected a limit of 5,000 words to ensure that the pixels devoted to each block were enough to display captions for each word.

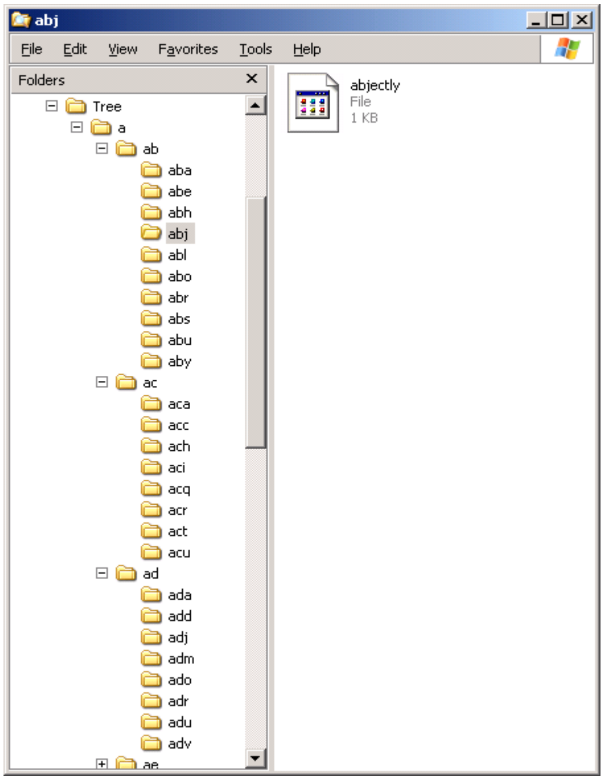


Figure 2. Hierarchical distribution of words

During our experiment design, the treemap algorithm did not use a lexicographical ordering for placement of the words. Instead, it used the number of leaf nodes under each tree and sub-tree to determine the exact location of a given non-leaf-node on the screen. From this random layout of words, we picked certain words for our experiment, taking care to include an even mix of words from the top, middle, and bottom of the screen as well as words overlapping bezel boundaries.

Material

To perform our performance evaluation, we used two physical displays, a 0.01 Giga-pixel display and a SMART Board™.

0.01 Giga-pixel display

Constituted of 3x3 tiled 17” high-resolution monitors each running at a resolution of 1280x1024 pixels (3840x3072 pixels total), this setup makes for an overall physical screen space of 3.75x3 feet. The display is connected to a Dell® computer at 2.66 GHz with 5 dual NVIDIA® GeForce FX 5200 video cards, and 2.00 GB of RAM (Figure 3). In addition, this tiled setup offered the flexibility to present the users with alternative screen configurations—a 2x2 tiled 17” high-resolution monitors each running at a resolution of 1280x1024 pixels (2560x2048 pixels total), for an overall physical screen space of 2.5x2 feet; and a single 17” high-resolution monitor running at a resolution of 1280x1024 pixels for an overall physical screen space of 1.25x1 feet.

Figure 3. The 3x3 tiled high-resolution display

SMART Board™

To study the effect associated with resolution and DPI, we decided to use a SMART Board™ 3000i, a 66” screen with integrated XGA projector running at a resolution of 1280x1024 pixels, for an overall physical screen space of 4.75x3.67 feet. Associated to the display is a Dell® computer at 2.00 GHz with a NVIDIA® GeForce4 MX 420 video card, and 256 MB of RAM (Figure 4). To ensure the consistency of the input device between both configurations, we disabled the touch screen and forced the participants to use a mouse instead.

Performed Tasks

We hypothesize that for a given dataset, the combination of DPI, resolution, and navigation technique affect the performance time of users on tasks that involve navigating into hierarchically-structured data. Participants in the experimentation were asked to find three words using each combination of navigation technique and screen configuration:

- Details-all-the-time navigation approach on a high-resolution 3x3 tiled LCD,
- Drill-down navigation approach on a high-resolution 3x3 tiled LCD,

- Details-all-the-time navigation approach on a high-resolution 2x2 tiled LCD,
- Drill-down navigation approach on a high-resolution 2x2 tiled LCD,
- Details-on-demand approach on a high-resolution single LCD,
- Drill-down approach on a high-resolution single LCD,
- Details-on-demand approach on a SMART Board™, low-resolution single large screen,
- Drill-down approach on a SMART Board™, low-resolution single large screen.

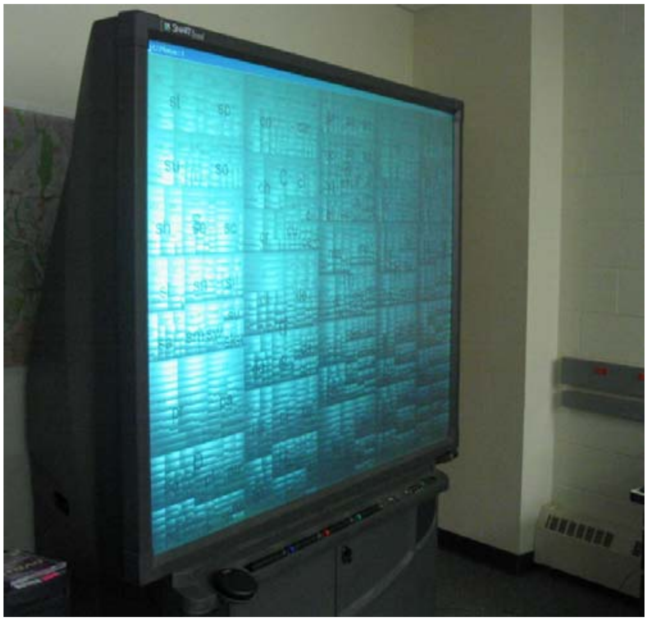


Figure 4. The SMART Board™

To ensure that results are not skewed by users gaining familiarity with one technique over another, we split them in two groups, one group performing the tasks in reverse order of the other.

Testing Procedure

To achieve a valuable performance evaluation and avoid bias resulting from user errors, we trained each user for a period of at least ten minutes to ensure they were comfortable with the evaluation tool, navigation techniques, and display configurations. The evaluators set up a new set of words, to ensure no spatial familiarity with the dataset resulting from the training. The participants were then presented a list of words and asked to find each using the predetermined configurations. Participants' performance time was then measured.

RESULTS AND ANALYSIS

Each user that performed a particular task was timed with a stopwatch. The shorter the time required for performing each task, the better their performance on that task. We compared the time taken by the users as an average per task. Apart from numerical measures of performance, we also asked open-ended questions to our participants to gauge their satisfaction levels with each display configuration. We also wished to uncover any specific problems that users encountered with a given configuration. We present our results based on a statistical analysis of the performance time—standard univariate ANOVA, post-hoc Tukey HSD pairwise comparisons, and log transform to conform with ANOVA assumption—as well as a summary of responses to the subjective questions.

Effect of Screen Size Using Drill-down Navigation

In our first experiment, we compared the effect of physical screen size on the performance time using a drill-down navigation technique. The DPI of configurations compared in this experiment was kept constant, while resolution was varied from 1280x1024 pixels to 3840x3072 pixels. As a direct result of changing resolution at constant DPI, the physical size of the displays varied.

Our evaluation showed that users perform much better using a drill-down navigation technique on a smaller display, as their performance time increases almost linearly as the screen size increases.

We attribute these performance differences to multiple factors. First, Fitt's law, as the screen size increases so does the distance to the target. Secondly, the relatively smaller size of the mouse pointer on a larger display. In fact, the small size of the on-screen pointer makes it difficult to spot and we found our users frequently searching for the pointer by vigorously moving the mouse from left to right and top to bottom and looking for any observable motion on the screen. Finally, an increase in graphic rendering time is also attributed to the high resolution of the display configuration (Figure 5).

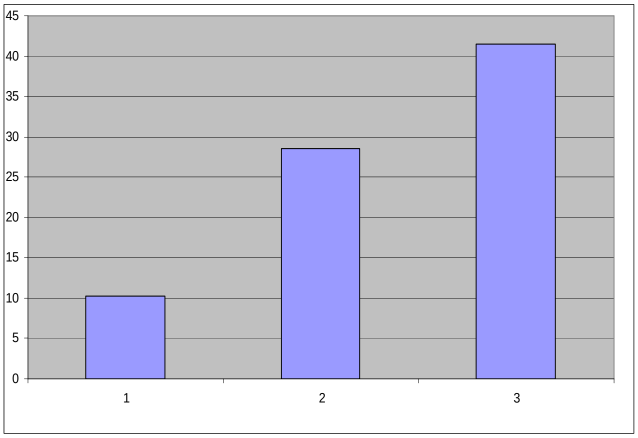


Figure 5. Average performance time given 3 display configurations using a drill-down navigation strategy

Compared to a single screen desktop configuration, the SMART Board™ has a lower DPI at the same resolution. Users performed almost two times faster using a drill-down navigation strategy on a single screen desktop display.

Because of lower DPI at constant resolution, even if the overall display surface increases, the relative mouse pointer size with respect to the display size is maintained so we cannot attribute this performance difference to Fitt's law. We believe that the larger physical surface area requires the user to visually scan a larger surface before and while making a movement with the mouse (Figure 6).

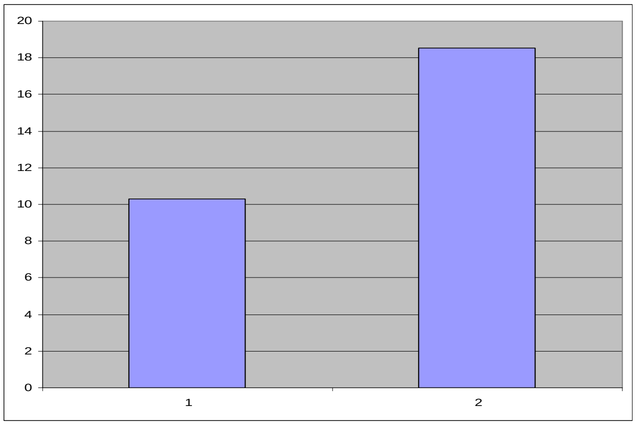


Figure 6. Average performance time on single monitor vs. SMART Board™ using a drill-down navigation strategy

Effect of Screen Size Using Details-all-the-time

In our second experiment, we compared the effect of physical screen size on the performance time using a details-all-the-time approach. The DPI of configurations compared in this experiment was kept constant, while resolution was varied from 1280x1024 pixels to 3840x3072 pixels. As a direct result of changing resolution at constant DPI, the physical size of the displays varied.

Our evaluation suggests a trend in performance increase as screen size increases. Users perform slightly better using a details-all-the-time approach on a larger display, as their performance time increases almost linearly as the screen size increases (Figure 7).

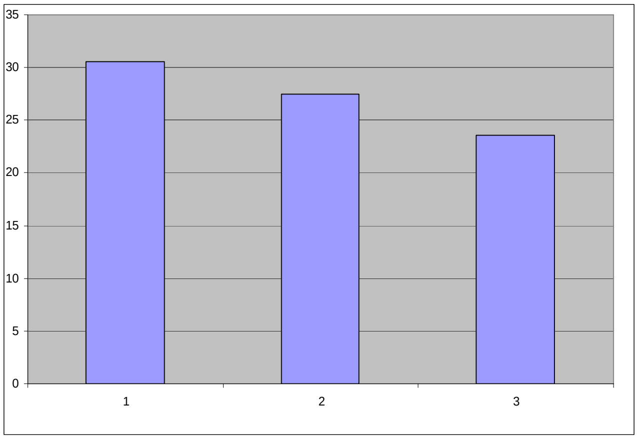


Figure 7. Average performance time given 3 display configurations using a details-all-the-time approach

Details-all-the-time vs. Drill-down navigation strategy

In our third experiment, we compared the performance time on an absolute timescale by varying resolution, DPI, and navigation techniques. Our study reveals that using a drill-down navigation strategy on a 1x1 high-resolution display results in the lowest average performance time and is therefore the fastest approach. When we consider different techniques on a 2x2 tiled display, the time taken for both navigations is almost equal: no conclusive inference can be drawn in this case. As display size further increases to 3x3 tiled display, we find that the details-all-the-time approach begins to show performance gains over the drill-down technique (Figure 8).

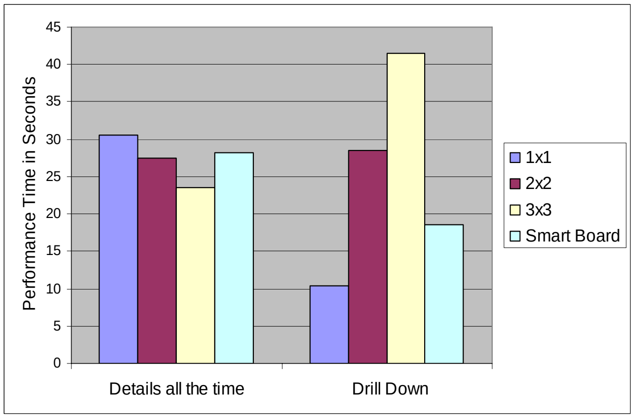


Figure 8. Absolute user performance time

We were limited to studying this trend to a 3x3 tiled display; however, extrapolating from the available results we can make a reasonable prediction that the details-all-the-time technique will result in increasingly better performance as display size increases to 4x4 or 5x5 tiled displays, assuming cognitive overload is not attained (Figure 9).

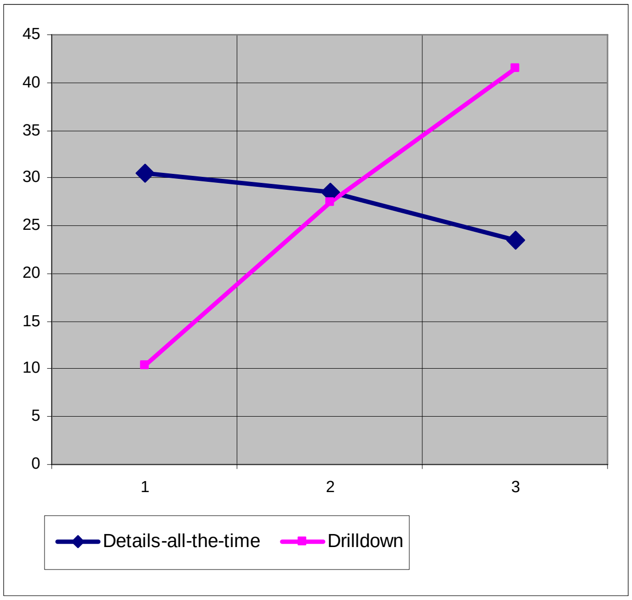


Figure 9. Effect of screen size and navigation technique on user performance

Impact of the Bezels upon User Performance

On the 0.01 Giga-pixel display, the impact of the bezel upon user performance can be seen as a benefit in some cases and can be a drawback in other situations. In fact, we observed people were working "one panel at a time", which was helpful in breaking down the screen structure and lowering the cognitive load. However, because of the bezel partitioning that screen real estate, participants often visually scanned a whole panel before realizing the container they were actually looking at was spread over several screens, which resulted in a performance overhead. For example, our experiment required users to spot the word "engrave" and were often misled by the word "engraver" which was more prominent but located on another panel. After unsuccessfully rescanning that panel, they discovered the container was spread over multiple panels (Figure 10). On a more positive note, we believe that the bezels promoted users to work "one panel at a time" resulting in a lower cognitive load. In fact, it provides spatial references allowing them to isolate their focus from the rest of the screen.

Figure 10. Containers spread over multiple panels separated by bezels

CONCLUSIONS

We conducted a study to discover if the data navigation techniques suitable for high-resolution displays differed significantly from those traditionally used for single screen desktop computers. The high resolution of the former display makes it possible to show more data at once rather than have the user drill-down to get to the details.

For a fixed dataset, we analyzed whether a display size suited to displaying the data entirely and comprehensively (and potentially increasing the cognitive load) was better performance-wise than a fixed screen size, forcing a user to drill-down to get to the details. In addition, we tested the scalability of two different navigation strategies in terms of DPI and resolution.

We proved that the larger physical size makes it difficult for the user to interact with techniques developed for smaller display, while the fastest performance was achieved on a small screen using a drill-down approach.

FUTURE WORK

We plan to extend our study using displays larger than the 3x3 tiled 17" high-resolution monitors, without bezel while supporting faster rendering as well as input techniques better suitable for large display such as touch screens. In addition, it would be valuable to perform a similar study based on insights.

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