

An Analysis of User Behavior on High-Resolution Tiled Displays

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Abstract. The use of multiple monitors for personal desktop computing is becoming more prevalent as the price of display technology decreases. The use of two monitors for a single desktop has been shown to have performance improvement in several studies. However, few studies have been performed with more than three monitors. As a result, we report an observational analysis of the use of a large tiled display containing nine monitors (in a 3x3 matrix). The total resolution of the large display is 3840x3072, for a total of 11,796,480 pixels. Over the course of six months we observed the behavior and actions of five users who used the display extensively as a desktop, and of 65 people who used the display during three other controlled experiments. We relate our observations, provide feedback concerning common usage of how people do and do not use the display, provide common scenarios and results of interviews, and give a series of design recommendations and guidelines for future designers of applications for high-resolution, tiled displays.

Introduction

Historically, large high-resolution tiled displays have been reserved for control rooms and large government facilities. However, using multiple monitors for one computer is becoming more common in both business and home life as monitors become less expensive and more research is done on productivity gains. With a small amount of extra effort and cost, a single computer can operate several monitors. For example, Microsoft Windows easily supports up to 10 monitors on a single machine.



Fig. 1. Picture of the tiled display used in this analysis

Tiled displays, with greater numbers of pixels, have the potential to increase the quantity and granularity of displayed information. They allow more information, more applications, and high-resolution images and visualizations to be viewed. Along with additional screen space, they pose problems of being physically larger and more difficult to navigate. They are large and cumbersome and often have bezels between tiled monitors that distort the image (see Figure 1). A bezel is the plastic covering around the edges of the monitors.

Many people often prefer multiple monitors to one monitor for a variety of reasons. In one particular study, Jonathan Grudin observed and interviewed 18 people who used two monitors on a daily basis [11]. He makes several conclusions that are insightful, but not extendable to larger displays. As will be shown, a large amount of work has been published that

indicates that larger displays consistently outperform smaller displays for a variety of tasks. However, little is known on how individuals' behavior differs from large high-resolution displays to one or two monitors. As such tiled displays are an emerging area of importance, significant HCI research is needed to examine how people perceive and interact with them.

Our motivation for this paper is to assess how large, high-resolution, tiled displays help individuals or small groups of users with everyday tasks, such as word processing, programming, and viewing images. Our goal is to gather initial basic evidence about how users adapt to the increased screen space and larger physical size of the displays, how they utilize the space and strategically organize their work, how they deal with the bezels between tiles, and the benefits and difficulties they have. In contrast to Grudin's insights, we performed a behavioral analysis that extends many of his observations and contradicts a few of them. We also make recommendations on how many monitors one should use, and how software user interfaces should be designed differently for large tiled displays.

In our analysis, a number of people extensively used a tiled display to view high-resolution images, GIS data, and perform rudimentary tasks such as using word processors, email clients, internet browsers, and spreadsheets over the course of six months. The display was also actively used for programming purposes, visualization assessment, and three HCI experiments [1].

This paper differs from other studies on large displays in two ways. First, this paper looks at the use of large, high-resolution displays, not just physically larger displays such as projectors. Second, this paper evaluates the use of such a display for a long period of time, not just for 30 minute to 1 hour segments. In this paper we explain previous work, our analysis method, key observations, and a list of suggestions for user interface designers.

Previous Work

A variety of studies have been performed on large screens and multiple screens to compare their effectiveness to that of small or single screens. Figure 2 visually shows the different categories of research on different types of displays. In general, there are two independent variables that researchers look at: physical size of the display, and resolution (total number of pixels, not pixel density) of the display. For example, in one corner of the space are standard projectors, with a large physical size but low 1 mega-pixel resolution. Whereas, in the opposite corner is IBM's T221 22.2 inch flat panel LCD that contains 9.2 million pixels.

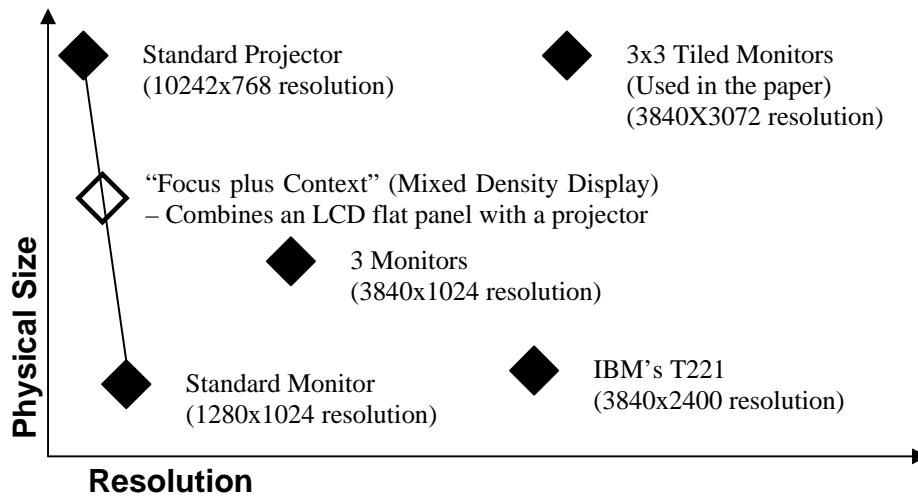


Fig. 2. The configuration space of displays, showing how several instances relate to each other with respect to physical size and total resolution (number of pixels).

Standard Projectors

Several studies have suggested that the increase of the physical size of a screen helps with memory. Lin, et al. [15] suggests that an increase of one's field of view increases one's sense of presence and memory.

How the idea of presence affects one's cognitive abilities is being thoroughly researched. Presence can be defined as to what degree one feels they are somewhere other than where they physically are [5]. Raja, et al. [22] suggests benefits of being surrounded by large low-resolution screens (CAVE) when dealing with data visualization (information visualization). They suggest that an increase of immersion and presence leads to better performance. For a background overview of presence, the reader might consult the following preliminary work: [2] [26].

Tan et al. show how performance on a large low-resolution screen can be better than a conventional small screen even at the same resolution. They show that with the same visual angle participants in a study were able to perform better on a large screen compared to a single monitor for both spatial performance [31] and 3D virtual navigation [30]. However, large low-resolution screens have the problem that they can only show the same amount of data as small screens because they have similar resolutions. As a result, the data on the screen is simply enlarged.

Other studies that involve more than one monitor generally focus primarily on multi-tasking or memory improvement. Other related studies have focused more on characterizing any benefits that one might receive from larger screens. These studies tend to focus on multi-tasking using current applications.

Standard Monitors

Terri Simmons [28] conducted a study comparing performance on different-sized monitors (17 inch to 21 inch), with slightly differing resolutions. His results were unsurprising in that they suggest that people perform faster with the largest monitor, and slightly higher resolution, as opposed to the smaller monitors.

Two to Three Monitors

Czerwinski et al. [6] explain the current state of performance measurements and explain that their own study showed conclusively that participants using a multi-monitor configuration affording increased resolution (3 monitors wide) performed better than on a single monitor. Tan, et al. [32] also show how retention can be increased by using extra screen space to display different images in the user's periphery to help recall more from a particular task session using their prototype called Infocockpit. They account for this increase of retention due to the increase of presence. In addition to using 3 monitors, they also use a projector as a background to help memory retention.

Some studies have also shown that gender can have an affect with spatial performance with screens. Some recent studies by Czerwinski, Tan, and Robertson show that the affects of an increase of field of view can offset the gender bias [29] [7]. Their findings indicate that women need a wider field of view than men to achieve the same performance.

Mixed Density Displays

In a unique study, Baudisch et al. [3] performed an experiment using their "Focus plus Context" screen to study the affects of having a small LCD screen embedded within a large projection screen (both standard low-resolution). In effect, they created a focus+context visualization using pixel density distortion instead of spatial distortion. They conclusively showed that participants were able to perform better while using their mixed-density display than with standard monitors and a variety of navigation strategies.

Large Tiled Displays

Few studies have reported findings on large tiled displays. Guimbretière, et al. [12] describe new interactive techniques for direct pen-based interaction on high-resolution displays, and reviews several other interaction techniques. A preliminary study on basic perceptual and navigational techniques shows that for fine-detailed information it is faster to find and compare information on high-resolution displays than low-resolution displays [1].

Our behavioral analysis falls into this category. Since little is known about how people use large high-resolution tiled displays, we chose to observe a variety of people using it for common tasks in a longitudinal study.

Analysis Method

In order to analyze everyday use of a physically larger, high-resolution display, we first constructed a 3x3 tiled display of LCD flat panels approximately 37 inches (94 cm) tall. We put the display on a standard desktop table approximately 30 inches (76 cm) off the ground. We then allowed a variety of people to use it, and observed its use over a six month period.

With modern plug and play technology, creating a large high-resolution tiled display takes relatively little expertise and is fairly low cost. Modern operating systems such as Windows and Linux have built-in support for multiple monitors. Windows XP supports up to 10 monitors and Linux supports any number of monitors - depending on individual system resources.

Our tiled display was constructed from nine 17" Dell monitors affixed to a wooden frame (see figure 3). We used one computer, a Dell Optiplex GX270, to support all nine monitors. In addition to the dual head AGP video card that came with the computer we installed four additional PCI video cards. All video cards were NVidia GeForce FX 5200. The approximate cost of the additional eight monitors and four graphics cards was about \$5,000.00 (US).

Figure 3 show various aspects of the tiled display. The picture on the left shows a side angle of the monitors as mounted on a wood frame. The same display could also be mounted on a supported wall or other more permanent place. However, we desired to have a display that could be easily relocated or adjusted. The picture on the right shows a front view of the tiled display with one of the monitors removed to show the underlying frame.



Fig. 3. The left figure shows the side view of the tiled display, showing how the monitors connect to the frame. The right figure shows the front view of the tiled display, with one monitor disconnected to show the underlying wooden frame. The sole computer powering the display is shown to the right

Five participants used the nine-monitor tiled display for at least three months in a form of time sharing. These users will be referred to hereafter as power users. One power user was designated time to use the tiled display during morning and early afternoon and used it as his primary workspace while the other four participants routinely reserved time during all other hours of the day and night on a first come, first serve basis as a secondary workspace. Each of these participants were researchers that used the tiled display for a variety of reasons from normal daily activities such as reading/writing email, browsing the Internet, writing papers, programming, viewing images, and running experiments. Each of these participants was a graduate student conducting research in computer science. In addition, there were four undergraduate users that used it for collaboration work in setting up experiments in groups of two that also used the display on a first come first serve basis after the first three months of the analysis.

During the six month period we performed three experiments on how well individuals performed and interacted on the tiled display at different configurations – using one, four, and nine monitors. Although these experiments were not done for the purpose of this paper, we were able to take our observations from the different experiments and apply them here. There were approximately 65 individuals that participated in the three experiments. Each of these individuals spent between 30 minutes to an hour interacting with the tiled display.

Our analysis also draws from our experiences with dozens of other people that were given demonstrations. Such people included high school students, people from the community, government officials, business professionals, and university students, faculty and staff.

Our observations in this paper are a result of a broad range of observations with the above mentioned people, ranging in form from the following methods:

- Direct observations as individuals interact with the tiled display.
- Formal interviews involving question and answer.
- Informal interviews to let the user talk about their experience without asking leading questions.

Observations

This section enumerates key observations during the course of our analysis. The topics include performance, spatial document positioning, bezel adaptations, adjustment period, wasted space, collaboration usage, maximizing an application, application focus, games and presentations, navigational issues, and physical size and layout.

Performance

From the previous work section, many researchers have shown the advantages of having larger displays. Several researchers have shown that larger displays improve performance with different tasks including multi-tasking [6], cognitive memory [34], spatial orientation [31], and general usability [28][11] to name a few.

Our observations show that users clearly referenced back and forth between primary tasks and secondary tasks on a regular basis. Also, interviews show that people reported having to do less window management and were more satisfied with the display as a result.

Our experience concurs with [11], showing that having a larger high-resolution desktop decreases the time switching between applications, allowing for a decrease in cognitive load. When a user is performing a specific task they often have the need for supporting tasks. For example, when writing a document, support information (e.g. references) is often needed. By having extra screen space, a user is capable of simply glancing at the supporting information instead of the need of switching between applications. By not performing extra virtual navigation, less concentration is lost. We observed referencing mainly with Internet browsing, programming, writing documents, writing email, comparing images, and comparing documents.

Although Grudin did not quantify by how much, we concur that “[w]hen a second monitor displays processes that support the primary task, it reduces the cognitive load by allowing rapid glances to check on information” [11]. We found the same to be true to a larger extent in that it is true not just for comparing from one monitor to another, but from one region of the screen to several others where each region may be larger than one monitor.

Another example of decreased cognitive load is viewing large images and visualizations. Many large images are too large for the entire image to be shown at once on one or two monitors, requiring additional navigation to see the entire image. With a large display there often is no need to navigate the image as the entire image can be seen all at once, allowing the user to spend all of his cognitive resources on examining the image. Even for very large images that cannot be displayed all at once on the tiled display, larger amounts of time can be spent without navigating as the user can spend more time studying larger sections of the image.

More Viewable Information at Once

With an increase in screen space comes many different opportunities for increased spatial positioning. With one monitor, users can only have a few applications viewable at a time. When a user has several applications viewable at a time only a small part of each application can be seen. In contrast, with multiple monitors there arises an opportunity to not only have more applications viewable, but have each of those applications taking up more screen space than is available to one monitor.

Our actual observations show that users often take advantage of the increased screen space. An observed scenario that represents common usage among most users follows: A user logs into the machine running the large display. He then opens up his remote desktop (for the purpose of using his own email client) and positions it in the lower-right monitor as he always does. He then opens a word processor to continue writing a report. Over the course of writing his report he also opens three Internet browsers, and a spread sheet. All the different opened applications, including the remote desktop, support his main task of writing the report. The different applications each occupy a monitor with the remote desktop always remaining in the lower-right monitor and his word processor always being in the middle monitor. The only applications that overlap each other are the Internet browsers.

This actual scenario taken from a session of a user that uses the display as a secondary workplace accurately represents most users. Key results from observations and interviews show that users prefer to use the middle monitor for their main application, surround the main application with support applications, and maintain constant positioning for certain applications (e.g. The remote desktop, email, instant messengers, etc.).

Two examples of using the increased screen space can be seen in figure 4. The picture on the left shows three PDF applications open side by side. Three different conference papers are viewed simultaneously allowing for easy comparisons of the documents. The picture on the right is a picture of actual usage while programming. Several applications can be seen including a command prompt for compiling purposes in the center, several programming editors, and one file explorer.

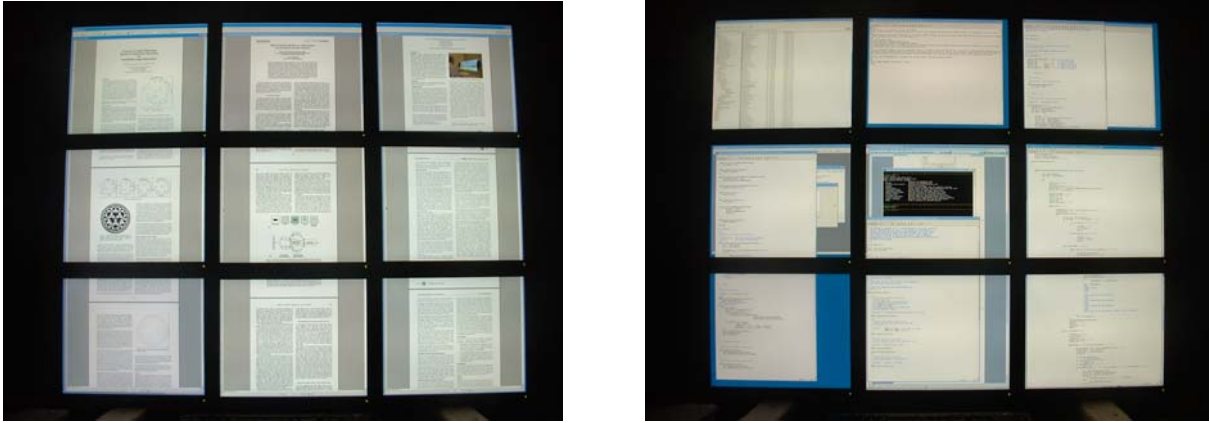


Fig. 4. The picture on the left shows three documents being displayed at once for easy comparison. The picture on the right shows a user's programming environment.

Categorization of Regions

After time, users tend to dedicate certain regions of the screen for certain applications. For example, one power user always positioned his email client application on the middle-right monitor while another power user always positioned his remote desktop (to get to his email client) on the lower-right monitor. After a period of time, users tend to develop preferences of where certain applications should be located. This preference of positioning applications in the same place relies on people's spatial memory abilities. This use of spatial memory is similar to the concept explored in Robertson's Data Mountain [24].

This use of positioning of applications was also observed to follow categories. In other words, power users tended to keep many personal or nonessential tasks in the same regions of the screen. Email, calendars, and instant messengers tended to have positions that were further away from the center of the screen and more toward the periphery. It was also observed that power users followed a pattern of keeping their primary application, the application with their primary focus, in the center column. Supporting tasks tended to be positioned around the primary task on the right, left, and below. This form of categorizing extends the observations of [11] from two monitors to nine tiled monitors.

This natural categorization is similar to what Kandogan attempts to do in Elastic windows [9]. However, where Kandogan attempts to improve user performance by categorizing windows on one monitor, we observed that people tend to categorize things naturally when they have more screen space.

Focus on Center

The primary task at any given time with the tiled display tended to be in the center column of the tiled display. It was observed that if a secondary application that was initially further away from the center column became more important and commanded more attention then it tended to be moved closer to the center column.

We hypothesize that the reason for applications to migrate toward the center is based on the physical positioning of the user, monitors, and input devices. Although users could easily turn their body toward any part of the display, the keyboard and mouse were not so quickly adjustable. It would become uncomfortable to have one's body pointed toward one part of the screen, say the right column, and have one's hands typing on a keyboard toward the center column. As a result, an application would be moved toward the center column after a period of time to make the user more comfortable. Although a user could reposition the keyboard and mouse closer to the right column instead of the center one, this made using the left column of monitors difficult.

Bezel Adaptations

Bezels, the plastic border separating monitors, are often considered a distraction to users. Current LCD technology makes it very difficult to construct a large tiled display without bezels. However, interviews from users and observations appear to differ as to how much a distraction they are. Key results from observations and interviews show that users do not generally like bezels, but that they use them very efficiently to their advantage to align, segregate, and differentiate applications.

With a single monitor the bezel does not generally cause any concern and usually goes unnoticed. On the other hand, the bezels around tiled monitors are usually one of the first things that people notice. The thickness of the bezels between monitors is a limiting factor on how close monitors can be tiled. Ideally there would not be a boundary between monitors so that the user would not even realize that more than one monitor makes up the display. Some projection-based displays come very close to seamless tiles. However, tiled projector-based displays have other problems, including a higher maintenance cost, larger space considerations, potential reduced visual clarity, and a higher price. It would be interesting to see how the results in our analysis would be affected by a seamless tiled display.

Interviews from users indicate that bezels are an inconvenience, irritation, and a point of frustration. Users have pointed out that bezels can distort the size of a document or an image. This distortion gives documents or images an artificial lengthening and can be confusing. As one user explained, “It can be really tough to mentally block the bezels out of your mind.” A visual example of bezels splitting an image is displayed in figure 5.



Fig. 5. : Comparison of an image with and without bezels splitting up the image

However, our observations show that bezels tend to help users quickly segregate applications between monitors. A common scenario for all users, whether first time users or power users of the display follows: Users first open the primary application in the center monitor. Users then either maximize the application to fill the center monitor with the maximize button or drag the application by hand to approximately fill the center monitor. All subsequent applications that are opened are usually maximized in a monitor that is not in use.

Only the most experienced user, the power user who used the display as a primary workspace, consistently used applications across bezel boundaries. The primary power user gradually became more comfortable crossing bezel boundaries and was able to grow accustomed to text and images being separated by bezels over a course of months. In contrast, our observations and interviews show that most users were able to use bezels to separate applications from the first time they used the display.

[11] explains how having a separation between two monitors can actually be beneficial in separating tasks and applications. Through our study we have found that bezels can be considered both an advantage and a disadvantage.

Adjustment Period - From small to large

Key difficulties that first time and new users struggle with are moving beyond the paradigm of one monitor, finding the cursor, using space efficiently, learning how to maximize an application to all nine monitors, and other unpredicted behavior from diverse applications. Although not all users faced all these problems the struggles that we listed appear to be the most common.

One example scenario that took place is when a student showing a demo on the tiled display had two applications open. One application was a control panel driving the other application, which showed a visualization of data. The student had nine monitors of screen space, but only utilized one of them. The student had the two applications maximized to fit on the center monitor. The student wished to show all the different features of the visualization from the control panel. He constantly brought the control panel to the front (over the visualization application), modified one or two parameters and then brought the visualization back to the front. As the student had eight other monitors to use, he could have easily used another monitor to show and interact with the control panel without the need to block the visualization window. When asked about it, the student responded with surprise and simply had not considered the possibility of spreading out the application over multiple tiles. From thence, he used it across two monitors and later expressed appreciation for the improved usage.

Adjusting to the larger display takes a variable amount of time. For example, moving beyond the paradigm of using only one monitor usually took less than an hour while finding the best strategies to finding the cursor usually took several weeks to learn.

As learning how to use the display takes time and is not instantaneous, a new user may get discouraged by actual loss of productivity at first. As a few applications no longer appear to act as they did, or do not act as the new user would think, the

experience can be frustrating. Unlike the noted publications that claim performance boosts with larger displays, new users are not necessarily given a lengthy tutorial at the onset for each application they might use, as was the case in the publications.

Adjustment Period - From Large to Small

Although not intuitive, we have also noted a definite frustration when using smaller-sized displays after using the larger display for an extended period of time. One scenario from the primary workspace follows: After approximately four months of using only the tiled display as his desktop he encountered a time when he had to prepare for a presentation on a laptop. When trying to change a small program and write notes about the changes, he encountered a great deal of frustration when not being able to see both the program he was editing and the word processor he was using for taking notes at the same time. It was also necessary at the time to have several more applications open at the same time on the laptop and he found himself frustrated and confused as to how to best manage the different applications.

When using only one monitor one power user reported “feeling cramped.” Another power user said, “[I would] get really close to the laptop to make it bigger.” Users had unlearned their previous organization strategies and had difficulty relearning them.

[11] supports our claim that people do not like going back to smaller displays. People feel more confined when they do. Although not quantified, many users, including the participant’s in [11] agree with our assessment that they feel more productive and often purchase or want to purchase more monitors for home use.

Wasted Space

Unfortunately, as there is more screen space, more of it is wasted. We observed that, with multi-tasking, users rarely used all the space that is available in the tiled display. With the tiled display, at least one-third of the display at any time was not used. Generally, the area not used would be the top three monitors. The top three were infrequently used as it is much easier on the neck to look down at the lower three monitors than to look up to see the top three. For example, see Figure 6.

Interviewing users explained that looking at the top portion of the display while sitting was either considered uncomfortable or caused neck strain. Actual observations show that users seldom used the top three monitors for multi-tasking purposes. However, when viewing images users often would stretch an application to span all nine monitors to view as much of the images as possible. When such applications were stretched to all nine monitors, the user would typically stand up at some point to see the top parts of the image well.

In comparison to one monitor, much more space is wasted as a percentage. In other words, where 100% of one monitor might be used most of the time (due to a single application being maximized), typically only about 50-60% of the tiled display is used at any particular time.

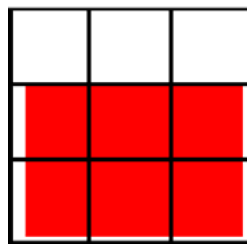


Fig. 6. For general multi-tasking purposes people seldom used the top three monitors.

Collaboration Usage

Through the increase in actual screen size, more people can gather around the display at once. However, although the display affords many uses for collaboration, we observed only the following collaborations in the order of most often to least often: image viewing, visualization viewing, Internet browsing, and document writing.

A common scenario: A normal scenario of collaboration usage is having one person sitting with either all others also sitting or all others standing. The one person sitting would control the display with the mouse and keyboard.

Another common scenario: Two people working on a document. One person drives the display while the other person is on the right of the first person. Most of the applications are found in four monitors to the bottom and right as any applications

found on the left of the person driving the display are hard to see for the person on the right. These users found it extremely helpful to be able to review long documents together by stretching the windows vertically across multiple monitors, and pointing with their hands to portions of the text. While one person was typing an edit, the other was able to look ahead in the document for other edits to make. The increased space also makes the possibility of multi-user input devices more attractive.

Maximizing an Application

There are several assumptions that operating system and application writers have made that do not hold true for displays of more than one monitor. Many different assumptions about having only one monitor have been made that appear anti-intuitive with several monitors.

For example, a scenario that occurred with almost every user follows: When a user tries to maximize an application across all nine monitors, they usually click on the “maximize” button in the top right-hand corner of the application. Most users expect to have the application maximize to the full screen size. However, what occurs is that the application maximizes to fill up a single monitor. After that, the behavior of the individual varies widely. Some users quickly realize that the only way to “maximize” a single application across all the monitors is to stretch it manually. Others take several minutes to realize this. A few people never figure out how to “maximize” across all screens on their own, and give up on trying if not given more help.

As a side, there exists software that can be installed on top of Windows that will allow users to maximize an application to the full extent of their display by clicking only one button. However, we have not seen such software available for other operating systems.

Application Focus

Filling out forms on a web page has become commonplace. Often web designers embed in the underlying HTML which text box or button should receive focus next. A user needs only fill in text, tab, then fill in the next text box. When all text boxes are completed the next widget that receives focus is usually the submit button. With one monitor it is usually fairly easy to see where the widget with the focus is. In the case that the next widget to receive focus is much farther down the web page then the browser automatically scrolls accordingly to bring the widget into view. However, with multiple monitors a web page may be extended across many monitors. In the example where the next widget to receive focus after a tab is farther down the page, the browser may not need to scroll as the widget is already viewable. Unfortunately, it may be difficult for the user to find where the focus actually is. On one monitor the act of searching the entire screen for the focus may be done quickly. However, on multiple monitors it may be a time-consuming process.

Similarly, when one is looking for a particular word in a document with the built-in *find* function, many applications scroll to the next word that matches the requested pattern and highlight the word. As in the previous example, scrolling may not be as necessary due to larger viewable area. A single highlighted word may be difficult to find. Some ‘find’ features enable users to only type in part of the word they are looking for to quicken the process. However, the smaller the pattern sought after, the smaller the portion of the text is highlighted. As a result, it may be very difficult to find the word, even when highlighted.

Another problem with applications is their dialogue boxes. Dialogue, or pop-up boxes, may appear any where on the screen space and may be difficult to find. Using only one monitor it is often trivial to find a dialogue box as there is very little area for it to appear. However, with multiple monitors, such as the tiled 9 that we used, it can be difficult to find or even notice that a dialogue box was opened if not expecting it. It has been the experience of some users to feel frustrated when suddenly it appears that their application is no longer responsive, when in fact there exists a modal dialogue box some where in the screen space that requires attention. The more applications open in the screen space, the harder it is to find. Many times, dialogue boxes were found only when the user was closing all applications to log off.

A cause of confusion to new users is where an application may appear on the screen when first started. Applications do not always open or start up where the user might expect. For example, if a user double-clicked on a shortcut located on the bottom right monitor, users generally expected the application to open in the bottom right monitor. However, the application almost always opens on the primary monitor if it the first time used, otherwise they generally open in the position where they were last closed.

After the first use, operating systems typically retain the previous location of the application, and restart the application at the previous size and position. This can be a benefit to users in that applications tend to open in the same place they were closed. However, on occasion there are times to only have one monitor operating for various reasons. If the application that the user wishes to use on only one monitor was positioned outside the primary monitor’s viewing area, it can be difficult to

move it back to the primary monitor for use. This can also be confusing to a user that can see that the application is open in the start bar but cannot actually get to the application. In Linux, sometimes the start bar itself is also on a different monitor and novice users are confused on how to even log out.

Games and Presentations

Applications such as games, DVD movie players, PowerPoint, etc. do not detect multiple monitors and different results occur. For instance, when a user is able to move an application, such as a DVD movie player application between monitors while the movie is playing, the DVD movie player application will only show on one monitor. For instance, if a DVD is playing and is shown on only one monitor and then moved to be positioned between two monitors, where half the application is on one monitor and the other half is on another, then the DVD movie player will still only show the movie on one monitor, displaying only black on the second monitor.

Games can have very different behaviors on multiple monitors. However, almost all games will only play on one monitor, usually on the primary monitor, and ignore the rest. One reason is that games often need to change the resolution of the monitor and does not have built-in support to do so on more than one monitor. Also, some games need the mouse to be positioned on the primary monitor, where the game will be played, or the user cannot interact with the game. The range of different behaviors of games is large and often is difficult to predict.

Hardware acceleration also is stopped when an application crosses graphics cards. As a result, 3D navigation applications appear to slow down by three or four times when forced to use software acceleration instead.

Interviews with users indicate that many users are initially excited about the idea of playing popular video games, or watching their favorite movie on the display. However, after trying to play games or watch movies on all nine monitors, disappointment results.

Navigational issues

Interviews with users, including power users and new users, indicate that losing one's mouse cursor on the screen is common and frustrating. To find the mouse cursor on the screen, users would perform one of the following common strategies, listed from most often used to least often used:

- quickly moving the mouse back and forth in a small area to use human visual motion detection,
- simply scanning the entire display until finding it, and
- moving the mouse to an extreme edge (e.g. moving the mouse down and right until finding it in the bottom right corner of the screen).

Using even two monitors at a time can lead to confusion when using a mouse. Simply put, users can easily lose track of where the cursor is on the screen. For nine monitors the problem is further exacerbated. Several ideas have risen to solve this problem, such as increasing the visibility of the mouse cursor at all times by Baudisch [4]. Baudisch's work is based on the idea of making the cursor more viewable during high-speed mouse movements when it is most susceptible to getting lost. Baudisch reduces the length of visual jumps that the cursor makes by essentially increasing the frame-rate to show smoother movement. This helps users keep track of where the cursor is.

Windows XP has a feature that helps the user to detect the mouse when it is lost. By pressing and releasing the "CTRL" key without any other key combination, an animated circle grows and shrinks around the cursor. However, our experience shows that such a feature is practically useless on a large tiled screen because the user has to be looking at the correct display tile to detect the animation. For example, if a user is looking for the cursor at the top right of the display and the cursor is in the bottom right then the animated circle cannot be seen by peripheral vision. A more visually salient animation is needed.

However, in general, less navigation is required in large high-resolution displays. By having a larger display, the needs to navigate at all are decreased. For example, as mentioned before, looking at a large high-resolution image, the entire image, or a greater percent of the image can be shown at once, thus decreasing the need to navigate as much as on a smaller display. The same is also true for documents, web browsing, etc.

Physical size and layout

A disadvantage of the high-resolution tiled display is its cumbersome physical size. Common questions such as where one should put the display are nontrivial. Often office space is considered sacred and not easily granted at many businesses and

universities. Although most tiled displays are tiled LCD's (liquid crystal displays), and thus take up less room than CRT's (cathode ray tubes), most tiled displays would not fit in office cubicles.

Also, there is a potential for additional physical stress and pain. If using a keyboard or a mouse for extended periods of time cause problems, then it is also logical that extended use with a large display may cause physical injury or discomfort to the neck or back although we have not observed any problems yet. More research is needed in this area before concluding anything about physical stress caused by large displays.

One inconvenience with using a large display is that there is usually only one mouse or keyboard that is used as input. Although we use an adjustable swivel chair to help users quickly move their body the mouse and keyboard do not move as well.

As described earlier, only 6 of our 9 monitors are usually in use. However, when displaying high-resolution graphics, or large pictures/spreadsheets, all 9 monitors are used. When such a situation takes place, standing is generally necessary to adequately view the upper portions of the image.

Suggestions and recommendations

Through the course of our analysis we have learned many things about the use of large high-resolution displays. In this section we discuss several suggestions and recommendations as guidance to future designers.

Number of Monitors and Physical Layout

Although biased, we concur with [11] that people should use two monitors as a minimum for each desktop. As a maximum, the layout and size of the monitors come into play. For example, experimenting with different layouts we found that six monitors side by side, (1x6 array) is very difficult to use. However, the same 6 monitors can be used very efficiently when stacked on top of each other in a 2x3 array (i.e. the bottom 2 rows of our display).

Several papers including [6] show performance increases with as few as two or three monitors. Also, Simmons [28] shows that just modestly increasing the resolution helps. [31] shows that just increasing the physical size is better for spatial performance. In general, abundant literature exists to show that modern desktop displays are inadequate for maximum performance.

As we have shown previously, we believe that unless a user has needs to view large images on a constant basis, no more than six monitors is recommended. This recommendation is based on physical size of the monitors and not on resolution density. However, with curved displays the number of useful monitors may increase. Also, new technology such as IBM's T221 monitor (nicknamed Big Bertha), which is 22.2 inches diagonal and has 9.3 million pixels (3840x2400), three monitors across may be unreasonable as the increased resolution would make scrolling the mouse across a horizontal resolution of 11520 pixels (3840 X 3) unreasonable.

Maximize Button

The current state of the maximize button feature does not extend to more than one monitor. As explained earlier, the maximize button may actually shrink the size of an application. One possible extension of the maximize button is, instead of just maximizing the current application to fit in one monitor, users should be able to easily select how many and which monitors to maximize across.

Floating Start Bar

Similar to marking menus [33], where the menu is dynamically called wherever needed, we suggest having the start bar pop up where and when the user desires. This way, regardless of how large the display it can be quickly accessible. Also, this would allow operating system programmers to leave the paradigm of a bar and have other shapes that might be more suitable such as a circle or a rectangle. Having floating start bars that are dynamically called would also allow more space to be used for displaying applications or images.

Use of Bezels

Bezels are the plastic surrounding the outside of monitors. Bezels provide natural separations between applications and tasks and can be regarded as helpful. Currently operating systems hide all knowledge of more than one monitor from applications. However, if applications were aware of where the monitor separations are they could take advantage of that information and display things more intelligently.

Users can also take advantage of bezels by segregating their work. As explained earlier, users reported using different regions of the screen to separate tasks and ideas. This concept can be taken farther by using bezels to also separate parts of the same application. As briefly mentioned by [11], movable taskbars can increase the amount of available screen space. Also, even with taskbars are not moveable, bezels can be used in such a way to increase work areas as can be seen in Figure 7. Internal sub-windows can be maximized to an entire tile, pushing toolbars and supporting frames across the bezel to other tiles.

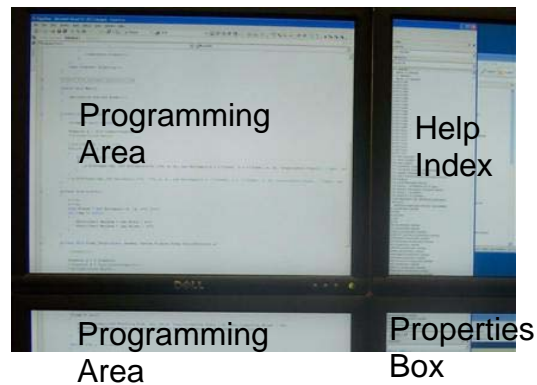


Fig. 7. An example of using bezels to separate work spaces in the Microsoft Visual Studio .NET programming environment.

Mouse

It is clear that the current state of interaction with the computer, with only the mouse as input, is inadequate. Interviewing users of another large tiled display (a display that uses approximately 40 tiled displays) from another organization confirms the need. For example, scrolling the mouse across 10 feet of high-resolution screen space is absurd.

One idea for overcoming the problem of scrolling large physical distances is to use the keyboard to quickly move the mouse across large areas of the screen. Hot keys could easily be created to move the mouse to an exact predefined position of the screen. This would help better facilitate finding the mouse as well moving the mouse quickly across large screen space. For instance, using our 9 monitors as an example, the key pad with the numbers 1 through 9 could act as hot keys for the mouse to position the mouse in the center of each of the monitors where each monitor corresponds to one of the numbers on the key pad. Alternatively, a multi-scale mouse feature might enable the mouse to be used to quickly select a monitor in course granularity mode, and then move within that monitor in normal fine granularity mode.

Also, finding the mouse can be problematic. One suggestion is to increase the size of the mouse or the animation finder to be more helpful. In Microsoft Windows' "CTRL" key solution, the animation circle size should be more noticeable and larger as the screen size is larger. It should also be customizable for different sized displays.

Another idea is having the cursor size on the screen grow and shrink depending on the acceleration of the mouse. For example, if the mouse is being moved quickly across the screen then the cursor size might temporarily grow large. This would allow people to more easily see the cursor during rapid movement.

For the time being, our recommendation to users for quickly locating one's mouse is simple. The user need only rapidly scroll to a corner. For example, if the user chose the bottom right corner of the screen then the user would rapidly scroll down and right. After about two quick scroll movements, the cursor can be found at the desired corner.

Of course, using other interactive techniques, such as laser pointers, pen-based interactions, touch sensitive panels, etc. may be more appropriate than using a mouse for large displays. Unfortunately, these other techniques are either found only in research environments or are prohibitively expensive for common use on large displays.

Conclusion

Our behavioral analysis shows that a large high-resolution display affords a number of advantages. This section summarizes the broad range of advantages and disadvantages explained in this paper. Advantages include:

- Improved user performance for task switching or viewing large documents
- Increased ability to spatially position applications and shortcuts for quick access and recall
- Bezel adaptations for easy separation of tasks
- Increased ability to work collaboratively
- Increased screen space for awareness for secondary tasks (e.g. Email, instant messengers, news, etc.)
- Enjoyment – interviewed users almost unanimously prefer multiple monitors to one

Disadvantages include:

- Adjustment periods (both from one monitor to multiple monitors, and vice versa)
- More screen space wasted
- Unpredicted behaviors with software applications
- Navigational issues with losing the mouse, input focus, or other highlights
- Physical size and layout may require more physical strain

Future Work

We intend to continue analyzing the basic perceptual and interactive issues of large high-resolution tiled displays. We intend to comparatively examine larger sizes and resolutions, tiled displays without bezels, greater pixel densities (such as IBM's Big Bertha display), as well as a range of interaction devices and techniques.

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