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ScienceDirect
Interacting with Computers 19 (2007) 151–166
Interacting with Computers
www.elsevier.com/locate/intcom

High-resolution gaming: Interfaces, notifications, and the user experience

Andrew J Sabri, Robert G Ball *, Alain Fabian, Saurabh Bhatia, Chris North

Center for Human-Computer Interaction, Department of Computer Science, Virginia Polytechnic Institute and State University,
660 McBryde Hall, Blacksburg, VA 24061, USA

Abstract

Advances in technology and display hardware have allowed the resolution of monitors – and video games – to incrementally improve over the past three decades. However, little research has been done in preparation for the resolutions that will be available in the future if this trend continues. We developed a number of display prototypes to explore the different aspects of gaming on large, high-resolution displays.

By running a series of experiments, we were not only able to evaluate the benefits of these displays for gaming, but also identify potential user interface and hardware issues that can arise. Building on these results, various interface designs were developed to better notify the user of passive and critical game information as well as to overcome difficulties with mouse-based interaction on these displays. Different display form factors and user input devices are also explored in order to determine how they can further enhance the gaming experience. In many cases, the new techniques can be applied to single-monitor games and solve the same problems in real-world, high-resolution applications.

Keywords: Games; Large displays; Notifications; Resolution; User interfaces; Multi-monitor

1. Introduction

With the rapid development of technology, the game industry has progressed from small one or two person development teams to studios that dedicate over 100 employees to a single game. As a result, the quality and detail of video game graphics have steadily improved with each new generation of hardware. The resolution[1] of personal computer monitors also continues to improve and even televisions are receiving more pixels with High-Definition sets. With these increases in rendering power and display resolution, graphics have become more realistic and have defined the success of many games.

The first arcade games ran at very low resolutions in comparison to the standard computer monitor found in households today. For instance, 1980's arcade games such as Pac-Man had a resolution of only 224 × 288, whereas common computer monitors today have a maximum resolution of around 1600 × 1200. By combining both a larger display and more pixels, the visuals, types of game-play, and overall user experience have improved over the last two decades. Now, even higher resolutions can be obtained by using multi-monitor display walls which are becoming more prevalent in the academic community.

Based on these observations, the multi-monitor display wall is a cost-effective prototype that demonstrates the potential for even higher resolution gaming. Just as with previous improvements of display-size and resolution, these setups have numerous benefits over their predecessors. For instance, the higher pixel-count enables more

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* Corresponding author. Tel.: +1 540 953 0229.
E-mail address: rgb6@vt.edu (R.G Ball).

[1] Historically, *resolution* is defined as *pixel density* in terms of dots per inch (dpi) on a computer-generated display. However, it has becomes increasingly common to define resolution as equivalent to *pixel count*. We will use this second definition throughout this paper.

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doi:10.1016/j.intcom.2006.08.002

sprites and 3D models to be displayed simultaneously with increased detail.

This study presents the results from two controlled experiments, usability evaluations, and user feedback. In both experiments, the participants played Wargus, a real-time strategy game based on WarCraft® II (see Fig. 1). The first experiment examined gamers in a series of competitive tournaments with different display sizes and resolutions. This study revealed the advantages of higher resolutions as well as a number of human-computer interaction factors, such as user interface issues. The second experiment evaluated four new notification and interruption techniques developed for high-resolution gaming as a result of the previous study. The paper then discusses a number of solutions we have developed to improve the usability of these new displays. Specifically, our research questions are:

- Do larger displays improve gamer performance? If so, how much improvement is gained by incremental increases in display size?
- What user interface, notification, and other usability issues arise on larger display configurations? How can these be solved?
- How can we achieve even higher resolutions? What other form factors and input devices can we use with these displays?

Our study shows that large, high-resolution displays greatly enhance the gaming experience. The majority of gamers preferred the dramatic increase in resolution and detail in comparison to the lower resolution version of the same games. We found that there are measurable benefits in that users score higher, require less virtual navigation, and have a greater awareness of the environment. By employing traditional usability experiments, user interface issues were both identified and resolved with new techniques developed to accommodate the larger display. As a result, gamers can enjoy the benefits of multi-monitor gaming without the user interface hindering the game-play. Surprisingly, these are some of the same issues that also hinder real-world, high-resolution applications. We also explore different display scalability issues, form factors, and input devices that could further enhance the user's experience with these displays.

2. Related work

There aren't many studies on gaming usability on high-resolution systems. However, as multiple monitor usage has increased, several studies have been performed to evaluate different aspects of larger and/or multiple displays for other applications. In general, these studies have focused on task performance for two to three monitors compared to one monitor or large projector-sized displays compared to one monitor.

For larger displays, such as projector-based displays, there have been several studies that have shown better performance on a larger display than a similar smaller counterpart. Such studies had tasks dealing with static data and have been shown an increase in memory (Lin et al., 2002; Tan et al., 2001), spatial performance (Tan et al., 2003b), 3D virtual navigation (Tan et al., 2004), and multi-tasking (Simmons and Fall, 2001). A few different interaction techniques have also been developed to use on large screens such as done by Mynatt et al. (1999) and Pedersen et al. (1993).

There have also been several studies showing improvements in user performance on multiple monitors. Such studies include an increase in performance in multi-tasking (Ball and North, 2005a; Czerwinski et al., 2003a), basic navigation (Ball and North, 2005b), and offset gender bias in performance (Czerwinski et al., 2003b; Tan et al., 2003a). There is also research studying how bezels, the discontinuities in a display surface caused by placing monitors side-by-side, effect how users interact with tiled displays.

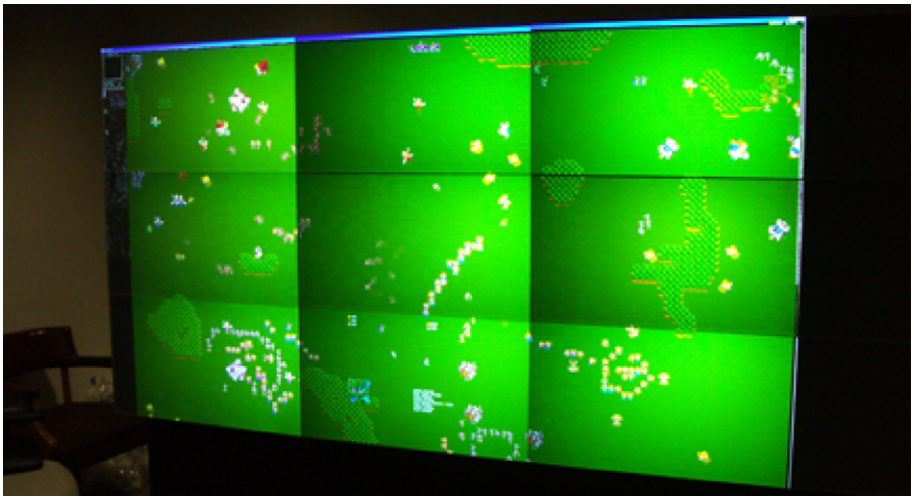

Fig. 1. Wargus, a real-time strategy game, being played on nine tiled screens at a resolution of 3840 × 2160.

These studies focus on bezel management (Mackinlay and Heer, 2004; Tan and Czerwinski, 2003) and window management (Hutchings and Stasko, 2004).

Results from Ball et al. (2005) show that users were significantly better at navigating static geographical maps and making informed decisions in geospatial environments. However, their study did not evaluate any form of dynamic data. Other studies have also looked at the displays themselves, such as the effects of a curved versus flat display (Shupp, 2006) and different display densities (Ni et al., 2006).

We explored the ideas of pen-, mouse- and touch-based approaches as described in Guimbretire et al. (2001); Baudisch et al. (2003); Tse et al. (2006) to develop new interaction techniques that would be better suited for high-resolution games. We also examined notification paradigms that are currently used in non-gaming applications that may be adaptable in notifying the user in games (McFarlane, 2002). Additionally, research done on animation and distance of notifications in the periphery (Bartram et al., 2003) is also closely related to gaming on large, high-resolution displays.

3. Experiment I

The goal of the first experiment was to investigate the impact of large, high-resolution displays on gamer performance and behavior. Multi-monitor desktops have been proven to improve performance in office productivity (Czerwinski et al., 2003a), however, little research has been conducted on their benefits specific to games. In addition to determining the benefits, we hypothesized that usability issues that result in scaling interfaces to higher resolutions could be identified with user evaluations and feedback.

3.1. Experiment design

We chose to use a real-time strategy game because of the similarity between such games and real-life scenarios of control room situations. Additionally, the point-and-click user interface commonly used in strategy games is similar to those in many desktop applications. We hope to show that large, high-resolution displays not only improve various aspects of gaming, but can be beneficial to other applications as well.

Table 1
Listing of the independent variables for the study

Display size	Map size
• 1 monitor (640 × 480)	• Small (2048 × 2048)
• 4 monitor (1600 × 1200)	• Medium (3072 × 3072)
• 9 monitor (2400 × 1800)	• Large (4096 × 4096)

Table 2
Listing of the dependent variables for the study

• Game score	• Wins and losses
• Time spent panning the map	• Usage of the minimap

In order to determine the benefits and short-comings of high-resolution displays, we compared three different display sizes consisting of one, four, and nine monitors (see Fig. 2). Additionally, we examined how changing the map size would effect our dependent variables (see Table 1). The dependent variables were chosen to determine whether changing screen- and map-size would effect gamer performance (see Table 2).

Using a tournament style approach, we held 10 competitions. There were three participants in each tournament (30 participants total) that played each other in a free-for-all game three times. Each participant would play on each of the three different display configurations. Participants were randomly assigned an initial display size and were given time to re-familiarize themselves with the game. Each experiment also contained a small, medium, and large map which was assigned randomly as well. We performed a full factorial design where all display-size orderings were completed five times. In other words, each participant played at each display once, so after six participants, we completed a full factorial of display orderings. Given that each participant used three different display sizes, participants were given time to familiarize themselves with their configuration before every game. Since we held 10 tournaments with three games per tournament, a total of 30 games were played.

Before tournaments began, participants were asked to fill out a questionnaire asking their age, gender, computer proficiency, and average number of hours they play video games a week. After each game, participants were asked to estimate approximately what percent of their time they thought they spent simply navigating the map. After all three games were completed, participants were asked which

Fig. 2. One-monitor (640 × 480), four-monitor (1600 × 1200), and nine-monitor configuration (2400 × 1800).

display size they preferred, and if the larger configurations helped and how.

3.2. Participants

For the study there were 30 participants that each had played at least 100 h in WarCraft II® or a similar real-time, strategy game prior to participation. Thus they were considered experts. All participants were between the ages of 18 and 23 with the average of 20. There were 35 male participants and one female participant. The average time playing games per week was 9-h-per-week ranging from 5 to 20+ average hours playing various games.

3.3. Game specifics

We used Wargus, an open-source project that uses WarCraft II® data and runs on the open-source game engine, Stratagus. Warcraft II® is a real-time, strategy game developed by Blizzard Entertainment.

Like most real-time, strategy games, Wargus is based on gathering resources, building up forces, attacking and destroying enemy armies. Players develop strategies to accomplish these tasks by evaluating the status of the units on the game map and the notifications presented on the screen. Users also must interact with and manipulate their units in various ways. For instance, users are able to select their army by clicking on individual units or by using a selection box to select multiple units. Each type of unit has different attributes and is controlled by buttons on the left side of the screen. Status information and notifications are located at the top and bottom of the display. Wargus uses the overview+detail navigation technique (see Fig. 3). In the minimap (overview), users can move the outlined rectangle that represents the position of the viewport by dragging it or by clicking on any area of the overview. Panning can be accomplished by using the arrow keys or mouse.

We altered the source code to track the dependent variables and made some changes to isolate the visual components of the game. As such, some features of the game such as sound notifications and fog of war were removed.

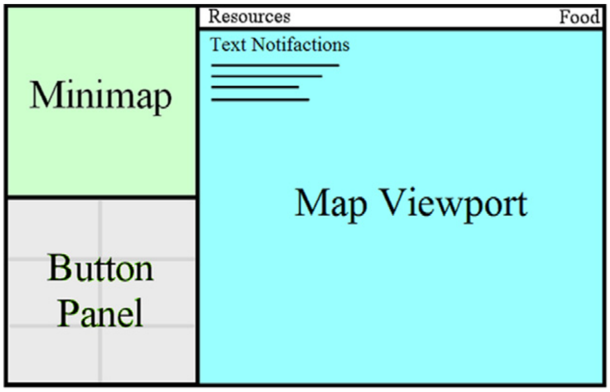

Fig. 3. A diagram showing the locations of the minimap, user interface, and viewport.

3.4. Hardware

For the experiment we used three computers with one, four, and nine monitors, respectively, as can be seen in Fig. 2. The one-monitor setup was set to have a resolution of 640 × 480 which is the default configuration for Wargus. The four-monitor computer had a resolution of 1600 × 1200 and the nine-monitor computer had a resolution of 2400 × 1800. Fig. 4 compares the relative size difference between the one- and nine-monitor configurations. The one-monitor configuration was kept at a low-resolution for the purpose of seeing how a higher resolution of the same game effects the user performance, navigation, and interface design of the original, unaltered game. On the nine-monitor configuration, 2400 × 1800 was the highest resolution we could obtain at the time while keeping the game at optimal speeds.

3.5. Quantitative results

This section explains the major results from our study. First, how performance (score and wins) is effected by screen resolution, second, how navigation is effected by screen resolution, and lastly, how navigation effects performance. All statistical analyses were performed in SAS's JMP using standard ANOVA and Chi Squared techniques.

3.6. Score and resolution size

Participants using the larger displays scored higher than the participants using the smaller configurations with a statistical significance of $p < 0.01$. The average score on the single monitor was 2207, approximately 20% less than the four and nine monitor configurations. The score for the four- and nine-monitor configurations were approximately equal, 2659 and 2790, respectively. There were no interaction effects between screen-size and map-size ($p = 0.76$).

3.7. Wins and resolution size

In addition to scoring higher, the participants also won more frequently on the larger, higher resolution displays. A player was considered the winner when both opponents were out of units and resources. As can be seen in Fig. 5, five of the 30 games (16.7%) played on the single-monitor setup resulted in a win, 12 of the 30 games (40.0%) played on the four-monitor setup resulted in wins and 13 out of the 30 games (43.3%) played on the nine-monitor setup resulted in wins. There were no ties. Performing a Chi Squared analysis, shows statistical significance of $p = 0.032$.

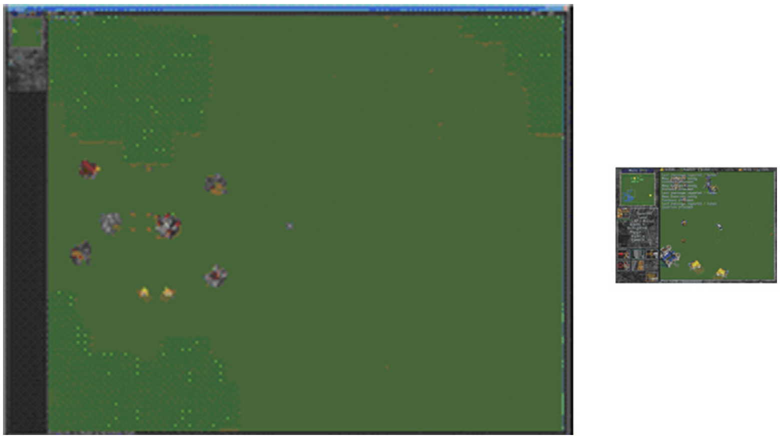

Fig. 4. Shows the difference in size between the one-monitor configuration (640 × 480) and the nine-monitor configuration (2400 × 1800).

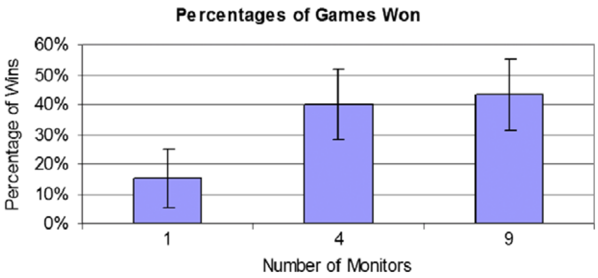

Fig. 5. The percentage of games that were won on the one-, four- and nine-monitor configurations. Larger sized screens won 2.5× more often than the small screen.

3.8. Navigation results

As explained earlier, we modified the open-source Stratagus graphics engine to track user input. Performing a two-way ANOVA of percent navigation revealed a main effect for display size ($p < 0.01$), a main effect for map size ($p = 0.02$), and no interaction effect between map-size and screen-size ($p = 0.36$). Percent navigation was calculated by dividing the amount of time spent navigating by the total length of the game.

Among our findings we found that the time spent navigating varied on the different displays. Specifically, the smaller the monitor configuration was, the more time the participant spent navigating. We observed participants navigating in the following way: On nine monitors, users navigated an average 5% of the game time; on four monitors, users navigated an average 10% of the game time; and on one monitor, users navigated an average 24% of the game time.

When comparing map- and screen-size (see Fig. 6), the amount of navigation varied across map sizes as well as display sizes. For example, on average there was little or no navigation on the nine monitors with the small map since the map was only slightly larger than the nine-monitor display. However, as the map-size increased, the amount of navigation also increased.

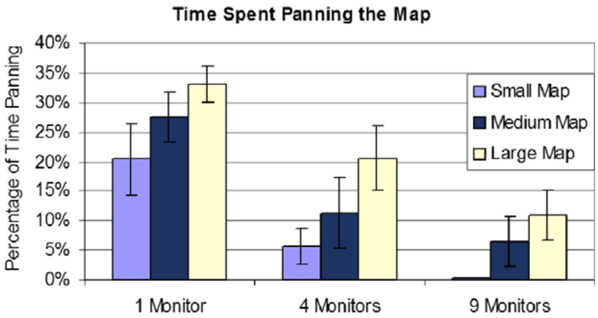

Fig. 6. Percentage of the time participants spent panning the map related to the size of the map- and screen-size. Single-monitor participants navigated five times more than nine-monitor participants.

3.9. Navigation time and performance

According to our results, time spent navigating effected score with a statistical significance of $p = 0.017$. Specifically, the less a participant navigated, the higher their score. Navigation also effected the frequency in which users won with a statistical significance of $p = 0.06$. As shown in Fig. 7, if the percentage of time that a participant navigated is presented in intervals, it can clearly been seen that the less a participant navigated, the more frequently they won. These results show that we can decrease navigation

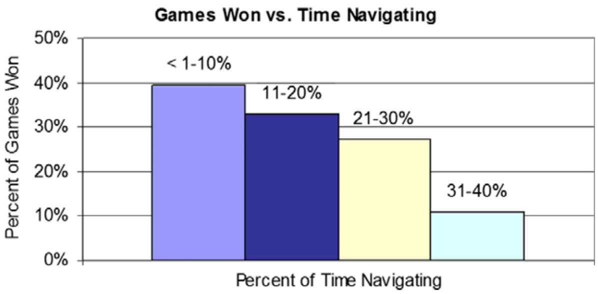

Fig. 7. This graph shows how the time navigating effected the percent of games won.

by increasing screen-size, and therefore increase user performance and allow the user to focus on game-play.

3.10. Overview interaction

By modifying the game engine, we were also able to track the interaction of the minimap, such as moving the viewport with the overview or issuing commands to units by right-clicking on the overview. With a statistical significance of $p < 0.001$, we found that the amount of times a participant would use the overview with the single monitor was greater than the four monitors, which was greater than the nine monitors. As seen in Fig. 8, participants used the overview less as the viewport-size increased.

Using nine monitors, a much larger area of the map can be seen by the user at once (see Fig. 9). By being able to see more context directly in the viewport, it was not necessary to navigate with the overview as much. Furthermore, since the minimap was located on the edge of the display, it required the large-screen users to move the cursor a much greater distance compared to the single-monitor user.

3.11. Qualitative results

We asked participants to respond to two questions: Which screen-size did you prefer the most and why? Did the larger configurations help you in any way? How? They responded to the first question in the following ways: Sixteen percent of the participants preferred the small screen-size over the larger screens. They stated that they were more familiar with the one-monitor configuration and disliked the bezels in the multi-monitor configurations. Sixty-three percent of the participants preferred the four screens. The different reasons follow: Much more of the battlefield could be seen than the one-monitor configuration. They felt that the nine-monitor configuration was too unfamiliar, and introduced problems in scalability of the original game's user interface. Twenty percent of the participants preferred the nine screens. Their reasons were that less navigation was required, it was easier to interact with their units, and they had a greater awareness of the map.

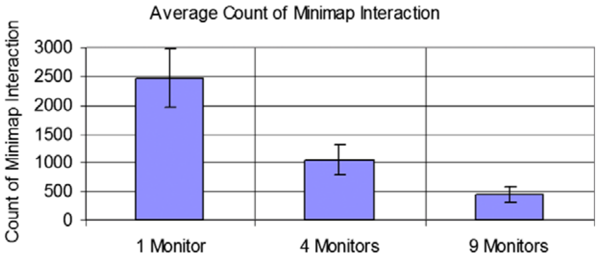

Fig. 8. The average number of times mouse interaction was detected in the overview per game.

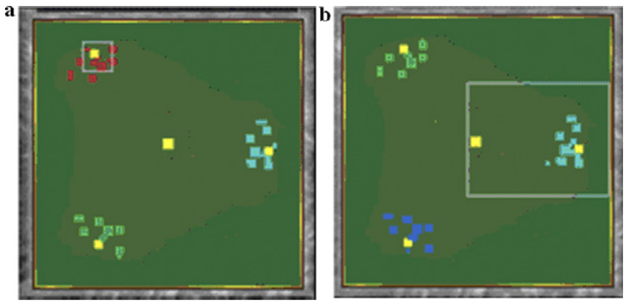

Fig. 9. (a) One-monitor overview (b) nine-monitor overview. The outlined rectangles in the overview show how much of the map the user can see. The one-monitor configuration sees only 5% of what the nine-monitor configuration sees.

In response to the question of whether the larger configurations helped and why, the vast majority agreed (90%) that it helped. They claimed an increased awareness of the entire battlefield, easier planning of strategies, and easier to interact with their units.

3.12. Notification systems and interface design issues

Seventy percent of the participants agreed that the notification systems and controls in the game were harder to use on the nine-monitor configuration and had a negative impact on their performance. In the game there are several types of notification systems and controls. Fig. 3 shows that there are several buttons as well as a minimap on the leftmost portion of the screen. On the top panel are several important statistics that report total resources and units. The bottom panel shows how much a potential unit costs when the mouse is hovered over the button that creates said unit. In addition, important messages are printed to the top-left of the viewport of the map.

All of these controls and notification systems are easy to use when they are close together. However, when using the nine-monitor display it was difficult for participants to move their cursor over to the control panel. Following Fitts' law (Card et al., 1983), it is more difficult to move the cursor to a target three screens away than it is to move a cursor to a target on a single screen. Thus, by increasing the distance to the control buttons and overview, it took participants much longer to accomplish basic game tasks on the nine-monitor display.

As mentioned above, the notification systems were positioned at the top of the whole display. Since the notifications were positioned above the participant's line of sight on the nine-monitor configuration, they claimed they didn't notice many – if any – of the alerts in the game. Since participants were not aware of vital events, such as needing more resources, we speculate that the poor positioning of the interface had an adverse effect on user satisfaction for the largest configuration.

3.13. Bezels

Although bezels were only 3/4 of an inch (1.9 cm) between monitors, several participants felt that the bezels were distracting. This was especially true on the four-monitor configuration where the intersection of bezels was in the middle of the display. Another problem with the bezels is that the spatial distortion caused participants to misinterpret the size of their armies and bases. Looking at the four-monitor display in Fig. 2, it appears that buildings that are on the bezel are wider than they actually are. Similarly, when a group of units crossed monitor boundaries it appeared that there were more units than actually existed. This illusion did not effect user performance as was found in Tan and Czerwinski (2003). However, Tan and Czerwinski (2003) did not identify the distraction reported by our participants. We speculate that the dynamic changes in the geospatial location of the data were the main causes for this reaction.

4. Experiment II

The previous experiment demonstrated that large, high-resolution displays introduce new challenges to the design of interactive systems. As these displays allow users to have an unprecedented amount of detailed information in their field-of-view, awareness of peripheral information becomes difficult. The dynamic and fast-paced environment of most games requires the user to focus attention to multiple areas of the display in addition to the user interface and notifications. In this experiment we investigate how we can reduce the problem of maintaining awareness of peripheral information without inhibiting the advantages of the additional pixels. To solve the problem of peripheral awareness, we propose bringing the notifications to the cursor during the game. Previous notification research shows that the ability to detect notifications in the periphery is significantly reduced the further away it is from the primary task (Bartram et al., 2003). Since most of the interaction with the game is done via the mouse, we assumed that this is the user's area of primary focus. (McFarlane, 2002) introduced four methods for coordinating interruptions which we believe offer four interesting design solutions for this technique.

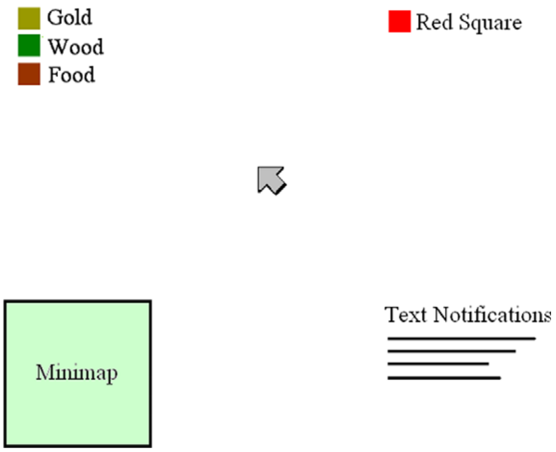

Fig. 10. Immediate design for Wargus. The resources are centered around the cursor.

4.1. Coordination of interruptions

McFarlane identified four methods to interrupt a user from a primary task: immediate, negotiated, mediated, and scheduled. We decided to apply this model of interruption to design notifications for Wargus by developing four different designs for bringing information into the user's focus. Our goal was to discover which design works best for informing users of important peripheral information on large, high-resolution displays.

4.2. Immediate design

In the immediate design, peripheral information is continuously displayed in the user's area of focus. Fig. 10 shows the resources centered around the cursor. As such, all the peripheral information follows the cursor at all times. This ensures that the user is constantly aware of this secondary information. However, it also obstructs the main focus area and may impact the performance on the primary task.

4.3. Negotiated design

In this design, the game information is brought to the cursor on demand (see Fig. 11). By default, the information is located on the top-left edge of the screen. However, users can have the game information displayed around the cursor at any time during the game by pressing the mouse's wheel button. The user can then send the information back to the default area of the screen with the mouse-wheel button again.

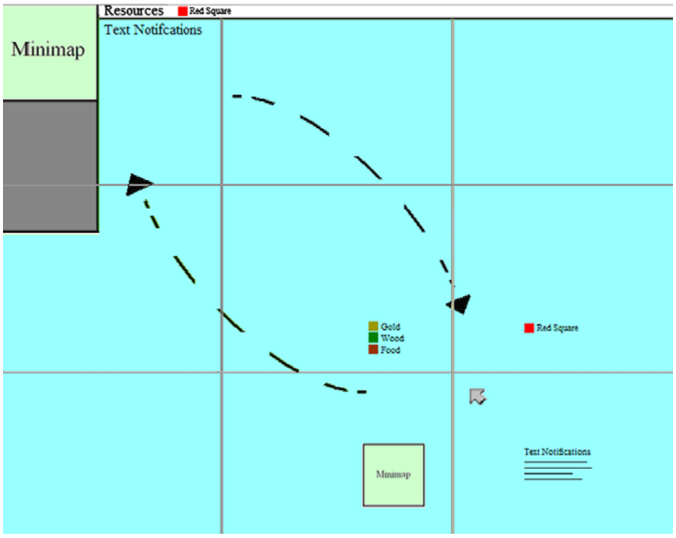

Fig. 11. A diagram demonstrating how the notifications are brought around the cursor. Each design brings the notifications into the user's focus a different way.

4.4. Mediated design

In this solution, the game information is displayed in the periphery by default. However, a simple computer algorithm constantly evaluates the best moment to interrupt the user based on their primary task status and their resource levels. Information will appear in the user's area of focus around the cursor when the computer determines it is necessary. For instance, information will appear in the user's periphery if gold level is low, when a user receives a text notification, when an event occurs on the minimap, etc.

4.5. Scheduled design

In this solution, the game information will, by default, be displayed in the periphery. However, the game information will appear in the user's area of focus every 30 s for duration of 10 s and then move back to the periphery. This allows the user to be interrupted to glance at their status for a short period of time.

4.6. Experiment setup

This second experiment required users to play one-on-one versus a computer opponent on a single, high-resolution display using the same game discussed in the first experiment. Each participant played a total of five games using a different notification design for each game. Participants were given a 30 min practice round where they could learn all five designs and re-familiarize themselves with the game. Each participant played all five designs in differing orders using a Latin square design. A total of 125 games were played.

To more accurately measure user awareness of peripheral information, we added an additional white square next to the game resources. Users were asked to press the space bar each time they saw the square's color change to red. The colored square followed the same behaviors as other resources in all conditions and was just described as an additional resource in the game. In the mediated solution, the square would appear next to the game cursor each time it turned red and was to be interpreted as critical. The red square appeared at random intervals a total of ten times each game.

For each design condition the following in-game data was tracked and stored for analysis and will serve as our dependent variables (see Table 3).

Each game lasted between 10 and 20 min with the total time of the experiment lasting approximately 2 h for each participant. Users were provided a sheet of paper showing common hot-keys and keyboard shortcuts used to build units, give commands, etc. At the end of the experiment, participants were asked to respond to a questionnaire. The questionnaire consisted of open-ended questions and used a seven-point Likert scale that enabled them to rate each design several ways.

Table 3
Lists the dependent variables for the study

- Game performance (score, game time, number of units killed)
- Resource monitoring performance (resource level maintenance)
- Red square monitoring performance (square detection)

4.7. Participants

We recruited 25 participants that had over 100 h of experience playing Warcraft® 2 or a similar real-time strategy game – we considered them to be experts. There were 24 male participants and one female participant, all with ages between 20 and 23. The user's had little familiarity with multi-monitor desktops, as they had an average value of 2.32 on a seven-point Likert scale (with 1 being the least familiar). A small number of users that participated in Experiment I also participated in this experiment. However, since the users were required to be experienced players and had only played a single game on the nine-monitor display, it is unlikely this had an effect on our results.

4.8. Hardware

The five different versions of Wargus ran on a display which used a 3 × 3 matrix of high-definition, rear projectors. The display provides a virtually seamless screen at a resolution of 3840 × 2160 and runs on a high-performance Dell server configured with five dual-head graphics cards (Fig. 12).

The original version of Wargus with unaltered notifications served as a control to discover whether any of the notification methods improved the original design and will be referred to as the *Standard* design. The game ran at a resolution that was 2.16 times higher than in the first experiment by using OpenGL to perform rendering across the five graphics cards. As a result, peripheral information such as gold, wood, and the minimap were even more distant from the user's focus area and more difficult to access visually. Additionally, by using projectors instead of LCD monitors, we were able to reduce the distance between each screen to one millimeter in an effort to eliminate the game-related problems bezels introduced in the first experiment.

4.9. Quantitative results

This section highlights how the four notification designs improved upon the standard system used in Wargus.

During the experiment, participants were asked to monitor a red square that would randomly appear near the other game notifications (Fig. 13). As such, the average response time for each design was tracked and analyzed. A standard ANOVA test suggests that there is a significant difference in the mean reaction time among the different designs ($p < 0.0001$). The designs that kept the critical game

Fig. 12. Wargus running on a rear-projection display at a resolution of 3840 × 2160.

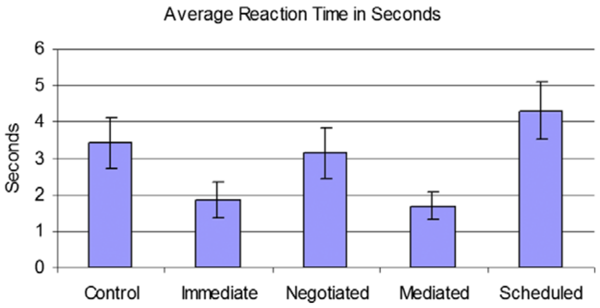

Fig. 13. This graph compares the average time it took for users to react to the red square notification for each design.

information in the user's focus at all times had much faster reaction times when detecting changes in the square.

Specifically, the mean reaction time for the mediated design was significantly faster than the reaction times for the Standard ($p < 0.0001$), Negotiated ($p < 0.0001$) and Scheduled ($p < 0.0001$) designs. So, by isolating the critical data and bringing it into the focus greatly helps improve a user's reaction time.

The mean reaction time for the Immediate design was also significantly faster than the reaction times for the Standard ($p < 0.0001$), Negotiated ($p < 0.0004$) and Scheduled ($p < 0.0001$) designs. Though it is not significantly different from the Mediated design, it shares the same benefits in reaction time, even while presenting non-critical in the focus simultaneously.

As each game had ten squares randomly appear, we can analyze how often users successfully detected (or missed) them as can be seen in Fig. 14. An ANOVA test shows significant differences in the average success rate for detecting the red square ($p < 0.0001$).

The mean detection rate for the Mediated design was significantly greater than the detection rates for Standard

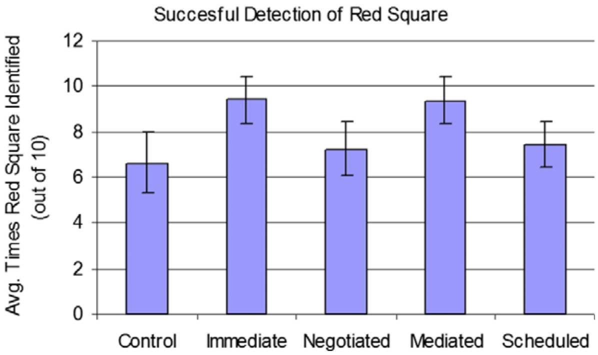

Fig. 14. This graph compares the average number of successful detections of the red square notification for each design. There were a total of ten notifications each game.

($p < 0.0002$), Negotiated ($p < 0.002$), and Scheduled ($p < 0.002$) designs. As with reaction time, the Mediated design allowed participants to successfully detect more squares by constantly keeping the critical data around the mouse than the designs that did not.

Just like the Mediated design, the mean detection rate for the Immediate design was significantly greater than the detection rates for Standard ($p < 0.0002$), Negotiated ($p < 0.002$), and Scheduled ($p < 0.002$) designs. Participants using both the Mediated and Immediate designs missed less than one red square on average. Just as with the reaction times, this shows that critical information can be shown along with passive game information without degradation of awareness.

We were also able to track the number of times users incorrectly hit the space bar when they thought they were being notified by the red square (see Fig. 15). ANOVA tests show significant differences in the number of falsely identified red squares ($p < 0.05$). The number of false hits for the Negotiated design was significantly greater than the Imme-

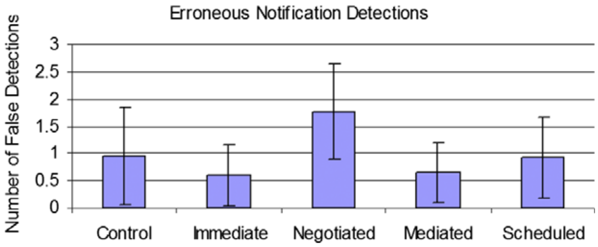

Fig. 15. This graph shows the average number of times users (inaccurately) hit the space bar when they thought the red square was present.

diate ($p < 0.008$) and Mediated designs ($p < 0.01$). This indicates that giving users control of when the notification is put in the focus creates an interesting issue. When compared to keeping critical information in the focus at all times, it can significantly cause users to erroneously detect notifications during the game.

Additionally, there was no statistically significant difference in regards to whether the four designs effected user score or other performance evaluations. While this does not demonstrate that any of the designs improve performance, we can state that notifying the users near the cursor does not negatively impact game performance with any significance. However, we can show that two of these methods do enhance the user experience on large, high-resolution displays qualitatively.

4.10. *Qualitative results*

This section highlights the participants' reactions to the four methods of maintaining awareness of peripheral information in comparison to the original game and each other.

4.11. *Immediate design responses*

All of the participants in the study liked how the information was always readily available without requiring them to divide their attention between different areas of the screen. They claimed that the design was consistent and reliable, so they always knew where to access the information they needed. The participants also claimed that the constant movement with the cursor was initially distracting to game-play, but this technique helped more than harmed. Users responded to this design in the following way: 93% felt it improved performance compared to standard design, 20% thought it was the best for detecting the square, and 24% preferred this design over the others.

4.12. *Negotiated design responses*

For this design, participants liked how they could have the information readily available on demand. Since the game information wasn't always around the cursor, it wasn't as distracting as the *Immediate* design. However, since the game data was not always in the user's focus, they commented that they often missed vital information. Users responded to this design in the following way: 72% felt it improved performance compared to standard design, 8% thought it was the best for detecting the square, and 20% preferred this design over the others.

4.13. *Mediated design responses*

By only showing pertinent information, users claimed it was easy to discern the information that was critical. The design also kept the information around the mouse uncluttered and it was much less distracting. Most also liked that the information would go away without any form of interaction. However, users claimed that not being able to access the data at all times made it very difficult to make higher-level decisions, plan future actions, and made the design inconsistent. Users responded to this design in the following way: 76% felt it improved performance compared to standard design, 72% thought it was the best for detecting the square, and 56% preferred this design over the others.

4.14. *Scheduled design responses*

We found that some users were able to learn when to expect the data to come into their field of view, but most found it to be unpredictable since they were focused on playing the game. The design divided their attention, and was highly interruptive at inappropriate points during the game. The design also caused them to miss critical information for the periods when it was not mapped to the cursor. Users responded to this design in the following way: 20% felt it improved performance compared to standard design, 0% thought it was the best for detecting the square, and 0% preferred this design over the others.

4.15. *General feedback*

With the written feedback received from our questionnaire, we were able to successfully evaluate how much each notification design effected the user's experience playing the game using a seven-point Likert scale. We found that there were no significant differences in how much the user perceived themselves to be interrupted with the *Standard*, *Immediate*, *Negotiated*, and *Mediated* designs (Fig. 16).

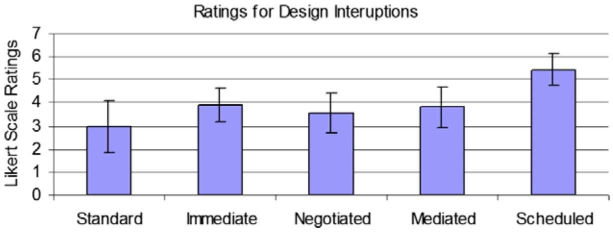

Fig. 16. Shows the Likert scale rating for how much the user felt the design interrupted them from their primary task.

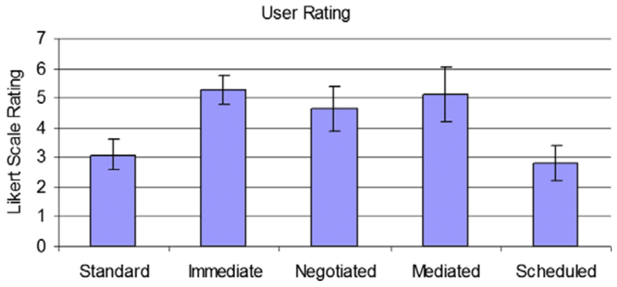

Fig. 17. The Likert scale rating for how much users preferred each design overall.

However, we did find that using ANOVA tests of the user interruption ratings for all designs suggests that there is a significant difference ($p < 0.0001$). User's found the Scheduled design more interruptive than the Standard ($p < 0.0001$), Immediate ($p < 0.0004$), Negotiated ($p < 0.0001$) and Mediated ($p < 0.0006$) designs. Users found that this design would intrude on their area of focus at inappropriate times and it severely interrupted them from their primary task of playing the game. The other designs were more subtle in their approach to notifying the user, and were not much more interruptive than the *Standard* condition. Due to this low-level of interruption, they were able to play the game without a substantial increase in interruption.

Users were also asked to rate each design for their overall preference using the same scale (see Fig. 17). A standard ANOVA test suggests significant differences in the users' overall rating of the different designs ($p < 0.0001$). The Standard design was rated significantly lower than the Immediate ($p < 0.0001$), Negotiated ($p < 0.0001$) and Mediated designs ($p < 0.0001$). With too little interruption in the Standard design, the users were unable to maintain comprehension of the peripheral information and it forced them to divide their attention away from the game. The Scheduled design was also rated significantly lower than the Immediate ($p < 0.0001$), Negotiated ($p < 0.0001$) and Mediated ($p < 0.0001$) designs. With too much interruption in the Scheduled design, users were distracted away from playing the game. Thus, by bringing the game information to the mouse without being too interruptive, we were able to increase the users' preference of this design compared to the Standard design.

Based on the written feedback, users indicated that they wanted a combination of both the Immediate and Mediated designs. They liked that they could see all of the game information all the time with the Immediate approach, but found the constant motion distracting. They also liked how the Mediated approach isolated what was interrupting the user and reduced the amount of information moving around the cursor, but wanted to be able to see all of the game information in the focus. The Negotiated approach caused users to miss important data and gave false clues to notifications. Finally, the Scheduled and Standard designs were, respectively, too interruptive or not interruptive enough. This user feedback gave us the data needed to design a notification system specifically for large, high-resolution gaming displays.

5. Proposed interface design

Based on the results from the two experiments, a new model for designing user interfaces for large, high-resolution games that use a mouse cursor for interface interaction can be developed. This section describes our final implementation and feedback for notifications and the user interface for gaming on these displays.

5.1. Visual notifications

The results from Experiment II show that displaying game information in the user's visual focus (near the mouse) does indeed increase their awareness of the game information. Though users preferred the Mediated design, their awareness was not significantly different than the Immediate design. Additionally, users claimed that not being able to see all the information (e.g. gold, wood, minimap, etc.) in their focus hindered them from planning strategies for the future. Furthermore, mapping information to the mouse cursor's constant movements was sometimes very distracting to the user. Past research also supports this claim in that "motion can contribute strongly to distraction and irritation" and "traveling motions are more distracting" (Bartram et al., 2003).

A solution to this on multi-monitor systems is to persistently display the all game data on the top-left corner of the active monitor the cursor is on (see Fig. 18). When the user moves the cursor to another monitor, the passive information will "transport" to the new active monitor. This allows the information to always be in the user's focus, significantly reduces the amount the information moves on the screen, and aids the user in making future decisions since all of the information is presented.

5.2. User interface interaction

There were also many issues with user interface interaction in both experiments. In the unaltered version of the user interface, the elements that can be interacted with (e.g. buttons, minimap) were positioned on the top-left area of the screen. When the resolution of the game was increased, the distance the mouse had to travel to interact with these elements also increased. According to Fitts' law, the time it takes to access this area of the screen will significantly increase as well. In fact, all of the users in the second experiment avoided using the interface altogether and opted to use the game's keyboard shortcuts instead.

The Standard interface design required users to move the cursor up to three screens vertically and horizontally to interact with the game controls and only becomes worse as more monitors are added. For this reason, we designed two new interaction techniques to be used in mouse-based

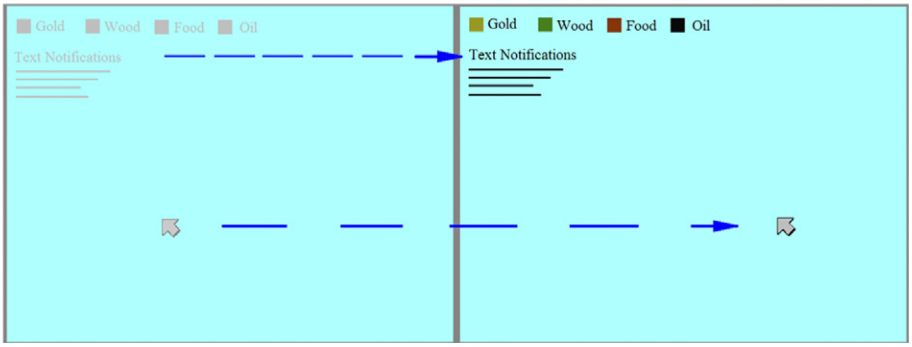

Fig. 18. This graphic shows how the notifications move to the active monitor the mouse is on so that the game information is always in the user's focus.

games to decrease the distance the user must move the mouse to access the user interface.

5.3. *Cursor-warp*

With this technique, all of the interactive elements of the UI are placed at the bottom and center of the display to be as close to the user as possible and not occlude the viewport. In order to give gamers rapid access to these controls, the middle-mouse button was implemented to "warp" the cursor directly to the user interface panel when pressed (see Fig. 19). The user can then make a selection on the button panel or minimap and then warp back to the original location of interest. This technique completely eliminates the need to physically move the mouse in order to access the UI. Fitts' law also no longer applies as the process of moving the cursor to the distant objects is instantaneous.

A few additional features needed to be implemented to make the design more intuitive. First, immediately after a user warps the cursor to the interface, a red animated square is placed at the original location of the cursor. This indicates to the user where the cursor will appear when they warp back. By using animation in the periphery, the user can more effectively maintain awareness (Bartram et al., 2003) of their original position. Additionally, a box was drawn around the area of the user interface that can be warped to. When the user moved the cursor outside of this box, both the box and the red blinking marker disappear. This feature was implemented when we discovered that users did not always want to warp the cursor back after interacting with the UI. This is to make it clear to the user that when they manually leave the interface without warping, and then attempt to warp, the cursor will be placed back on the UI.

There also were interesting side-effects that were observed in user testing of this design. For instance, users would often use the cursor warp when they wanted to move from one side of the display to the next as it essentially divided the distance they had to move the mouse in half. Additionally, many users claimed that this design would also benefit interaction with game interfaces of the computer games they currently play.

5.4. *UI-warp*

We also designed another technique to give the user rapid access to the button panel and minimap. This design takes a similar approach to the *Drag-and-Pop* and *Drag-and-Pick* techniques for styluses and touch panels (Baudisch, 2003). However, the *UI-Warp* design focuses on button-panel and overview interaction in applications with a standard mouse. By clicking the middle-mouse button, the interface will warp from the bottom-center monitor to the same relative location on the monitor the cursor is on. A second click of the middle-mouse button will warp

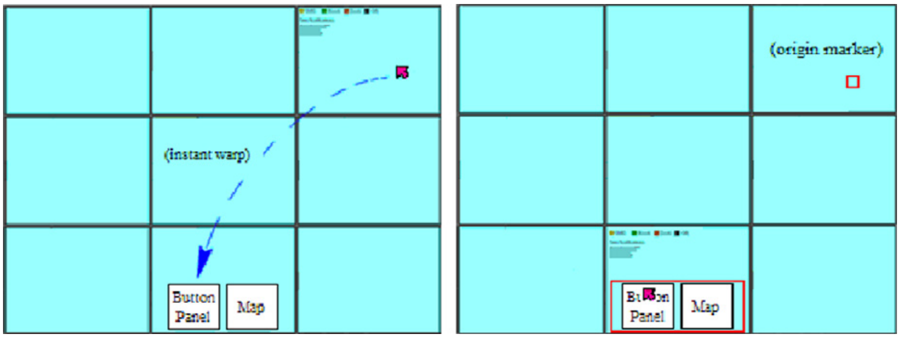

Fig. 19. Diagram demonstrating the "Cursor-Warp" technique. The first diagram shows the cursor warping to the button panel. The second diagram shows the cursor on the panel and a red marker where the cursor used to be. From here they can warp back to the red marker if they choose.

the UI back to its original location at the bottom of the screen. Using this method, the user is still required to move the cursor to the interface after each warp as they would on a single-monitor display – but the distance traveled is greatly reduced.

While access is not instantaneous as with the *Cursor-Warp*, this design has two main advantages. First, by bringing the interface to current area of focus, there user's attention is not divided and they can concentrate on their primary task. Second, it gives a simple and intuitive mechanism to place the user interface on the screen they prefer. For instance, if a user is building a base on the top-right screen and is interacting with the button panel frequently, they can warp the panel to that screen until the task is completed.

6. Gaming display systems and scalability

There are various ways to construct displays with higher resolutions. One such approach is IBM's "Big Bertha" monitor which has a resolution of 3840 × 2400 and looks similar to a traditional LCD display. While displays constructed in this fashion will come down in price in the near future, they cost several orders of magnitude more than current monitors. Our approach expands on the concept of the multi-monitor desktop and – with some minor trade-offs – is a comparatively inexpensive approach to increasing resolution.

The two experiments conducted each used a 3 × 3 matrix of nine monitors connected to a single personal computer. The computer had five dual-head graphics cards used to render the OpenGL graphics. The first experiment used conventional 17-in. (43.2 cm) Dell monitors with bezels 3/4 in. (1.9 cm) wide. The second experiment used configurable rear projectors instead of LCD screens. While this approach costs more, the bezel size was reduced to one millimeter in width and dramatically reduced the bezel issues encountered in the first experiment. However, most personal computers are limited to five or six PCI slots, so even with dual-head graphics cards, the hardware can only support up to twelve monitors. Additionally, there is a software limitation as Microsoft Windows® can only support up to ten monitors by default. Even if more monitors could be added, current upper-end desktop computers do not have sufficient processing power to drive them.

In order to circumvent these limitations, we constructed a twelve-node Linux cluster. Each node was a standard Dell desktop computer with a dual-head graphics card to create a twenty-four monitor display (see Fig. 20). The cluster uses the open-source Chromium software package to distribute the OpenGL graphics across a gigabit internal network to each of the nodes (Chromium). Using this approach, fast-paced 3D games such as Quake 3 and flight simulators can be played fluidly and in real-time at resolutions of 10240 × 3072. Although most consumers and gamers cannot afford the nine- or twenty-four monitor display systems we've constructed, our results and related work (e.g. [productivity – Czerwinski]) show that even having two monitors can be a huge gain in both performance and user satisfaction. The main benefit of these multi-monitor systems is their scalability. Gamers generally *can* afford one or two additional monitors and can continue to add more screens to their system as desired.

Fig. 20. Quake 3 being played on a curved, twenty-four monitor display wall.

7. Form factors and input devices

As was mentioned in previous the section, we were able to play Quake 3 Arena at a resolution of 10240 × 3072 on a configurable, multi-monitor display. Unlike games that use a mouse-based user interface, first-person shooters and flight simulators do not suffer from the same interface issues at high resolutions. In the case of Quake 3, only the values for ammo, health, and armor need to be displayed. By scaling them with the resolution and display size they can be observed quickly and accurately. Without user interface drawbacks, we were able to investigate other methods of enhancing the user experience for gaming on these displays.

Since our display wall is configurable, we experimented with curving the display around the user and changed the field-of-view in Quake 3 accordingly. In effect, users can see the gaming environment and objects (such as the red rail-gun laser in) in their peripheral vision. Volunteers using the curved display claimed that in addition to greatly enjoying the higher levels of detail, they felt much more immersed in the gaming environment than with the flat display.

Although CAVE's (Cruz-Neira et al., 1993) offer similar experiences of increased levels of presence and immersion, CAVE's are historically low-resolution. The result is that the environment is pixilated and blocky in comparison. Additionally, curving the display helped participants lower frustration levels and perform better in a geospatially-oriented experiment regardless of the viewport size (Shupp, 2006). Intuitively, by curving a large display the pixels are brought closer to the user and less detail is lost.

There are many benefits to playing first-person shooters on large, high-resolution displays, but there are also some issues that need to be resolved. First, while none of the volunteers initially complained about the bezels between the monitors, when asked about them most said they would prefer the gaps to be smaller. Also, the increased tempo of most first-person shooters on twenty-four monitors created too much rapidly changing detail for players to take in for extended periods of time. As a result, users – even experienced Quake 3 Arena players – got slightly dizzy after about an hour of gaming, especially when they were standing too close to the screen. However, this did not appear to be a problem with slower-paced games with similar detail levels.

In addition to curving the display, we found that certain interactive devices were more appropriate for use with multi-monitor walls compared to single-monitor desktop displays. One option for interacting with the displays in a gaming environment is via a touch-screen interface combined with voice-commands (Tse et al., 2006). However, this method does not translate well to simulations, first-person shooters, and other game genres. Instead, we had volunteers use and compare both a gyration mouse and an optical mouse. A gyration mouse is a wireless mouse that can be used without the need of a flat table surface (see Fig. 21). When holding the device, it tracks the user's hand movement in 3D-space with a gyroscope – resulting in an experience similar to wielding a pistol when used with a first-person shooter. We hypothesized that the gyration mouse would be a very natural fit for our display since it would allow gamers to exploit the full range of motion of their hand/arm and they wouldn't be restricted by the smaller size of a single monitor.

Users were asked to play several rounds of Quake 3 on the display wall with each mouse. All of the volunteers noted that they used an optical mouse daily and none had ever used a gyration mouse. As a result, when they used gyro mouse there was a steep initial learning curve in comparison to the optical mouse. However, after playing with both devices, all of the users preferred using the gyration mouse even though their performance decreased substantially in comparison to the optical mouse. Surprisingly, users did not experience hand and arm fatigue, even after about an hour of play-time, with the gyro mouse as we expected – though this is still likely to occur after extended periods of play.

8. Real-world applications

In addition to gaming, large displays have potential to improve in other areas of computing as well. The higher resolutions will allow flight and training simulators to be much more realistic and effective. Moreover, many control rooms are being outfitted with tiled, high-resolution display walls and workspaces as the cost of hardware continues to decrease. Some of these control room scenarios include: military command and control, satellite image analysis, emergency response coordination, power grid and infrastructure management, traffic analysis, and global weather monitoring.

By using video games on these displays, we were also able to successfully identify potential user interface and notification system issues for mouse-based computer games. As the majority of applications use a very similar control-button interface, the same issues would also occur when these applications are scaled to much higher resolutions. These issues include accessing distant interface objects and visually notifying the user without hindering their primary task. By using traditional usability studies to evaluate new game interface ideas, we were able to design solutions to not only solve these problems in gaming, but can be translated to real-world applications as well.

9. Conclusion

By performing a controlled usability experiment, we were able to determine that users perform better and prefer high-resolution, multi-monitor displays while playing a real-time, strategy game. Participants scored an average of 20% higher and won over twice as many games when using the larger displays. The improved participant performance is evidence of greater engagement, immersion, and

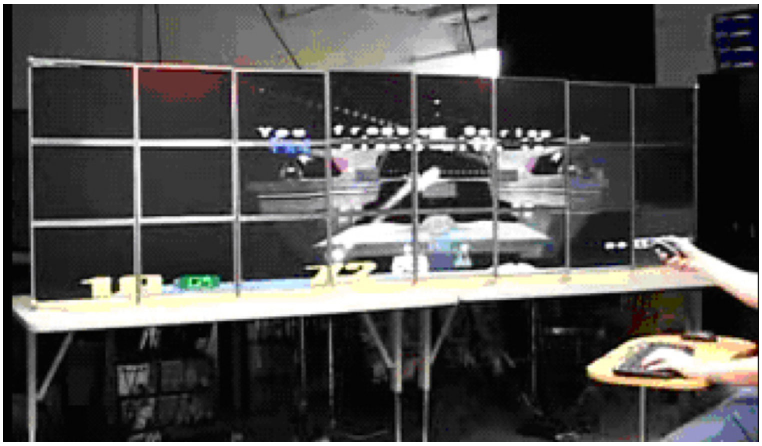

Fig. 21. Quake 3 being played on a flat 24-monitor display wall with a gyro mouse.

focus, with less distraction by tedious interface controls such as navigating.

We were also able to identify the user interface issues that arose on the larger display configurations. With 70% of participants complaining about these issues, the problem was worse than expected. Participants using the nine-monitor configuration could not effectively use the overview, see vital notifications, or interact with control buttons since they were placed on the far top-left edges of the screen. This required users to constantly observe the very top of the display for notifications and move their cursor across multiple monitors to accomplish simple tasks.

By conducting another experiment, we were able to compare four different approaches for solving the problem of visual notifications being too far in the periphery by bringing them to the mouse. We analyzed these approaches and found that users preferred to always have the game information in the area of the mouse cursor in a manner that was not significantly more interruptive than the standard game interface. It was also found that this method increased awareness by improving reaction times and successful detections of game notifications. It's also interesting to note that by giving the user control of when notifications should be in the focus caused more misinterpretations of the information than the other techniques.

Using the results from these two experiments, we were able to design a new notification system and greatly reduce overhead when interacting with button panels on high-resolution displays. The notifications now "transfer" to the active monitor that the cursor is moved to, keeping all the information in focus without being too distracting. The *Cursor-Warp* interaction technique allows uses to instantaneously interact with the button panel and mini-map by warping the mouse to these locations on demand. The *UI-Warp* technique accomplishes these same goals without dividing the attention of the user, but requires slightly more mouse movement than the *Cursor-Warp.*

We also discussed the hardware issues and scalability of multi-monitor gaming systems, as well as identified different form-factors and input devices that can improve the user experience on these displays. By having volunteers play Quake 3 on a curved, multi-monitor display with a gyration mouse, we found that – even though they performed notably worse with the new mouse – they had a much more enjoyable experience playing on the setup compared to a traditional mouse and a single-monitor desktop.

We found that while users welcomed the dramatic increase in detail, using the displays also had distinct measurable benefits such as higher scores, less virtual navigation, and greater awareness. With the introduction of new interaction techniques and input devices inspired by these displays, gamers could further enjoy the benefits of multi-monitor gaming. Overall, we found that large, high-resolution displays greatly enhanced the gaming experience and we hope that this research will inspire new, high-resolution display systems, higher quality graphics – and more importantly – innovative new game-play.

References

Ball, R., North, C., 2005. An analysis of user behavior on high-resolution tiled displays. In: Interact 2005 Tenth IFIP TC13 International Conference on Human-Computer Interaction. pp. 350–363.

Ball, R., North, C., 2005. Effects of tiled high-resolution display on basic visualization and navigation tasks. In: Extended abstracts of CHI '05. pp. 1196–1199.

Ball, R., Varghese, M., Carstensen, B., Cox, E.D., Fierer, C., Peterson, M., North, C., 2005. Evaluating the benefits of tiled displays for navigating maps. In: Proceedings of IASTED-HCI 2005.

Bartram, L., Ware, C., Calvert, T., 2003. Moticons: detection, distraction, and task. In: International Journal of Human-Computer Studies.

Baudisch, P., Cutrell, E., Robertson, G., 2003. High-density cursor: a visualization technique that helps users keep track of fast-moving mouse cursors. In: Proceedings of Interact 2003. Zurich, Switzerland, pp. 236–243.

Baudisch, P., 2003. Drag-and-Pop and Drag-and-Pick: techniques for accessing remote screen content on Touch-and Pen-operated Systems. INTERACT, 57–64.

Card, S., Moran, T., Newell, A., 1983. The Psychology of Human-Computer Interaction. Lawrence Erlbaum Associates, ISBN: 0898598591.

Chromium. http://chromium.sourceforge.net/.

Cruz-Neira, C., Sandin, D., DeFanti, T. 1993. Surround-screen projection-based virtual reality: The design and implementation of the cave. ACM SIGGRAPH '93.

Czerwinski, M., Smith, G., Regan, T., Meyers, B., Robertson, G., Starkweather, G., 2003. Toward characterizing the productivity benefits of very large displays. In: Proceedings of Interact 2003.

Czerwinski, M., Tan, D., Robertson, G., 2003. Women take a wider view. In: Proceedings of CHI '02. pp. 195–201.

Guimbretire, F., Stone, M., Winograd, T., 2001. Fluid interaction with high-resolution wall-size displays. In: Proceedings of UIST 2001. ACM, pp. 21–30.

Hutchings, D.R., Stasko, J., 2004. Revisiting display space management: understanding current practice to inform next-generation design. In: Graphics Interface 2004. Canadian Human-Computer Communications Society, pp. 127–134.

Lin, J. J.-W., Duh, H.B., Parker, D.E., Abi-Rached, H., Furness, T.A., 2002. Effects of view on presence enjoyment, memory, and simulator sickness in a virtual environment. In: Proceedings of IEEE Virtual Reality.

Mackinlay, J.D., Heer, J., 2004. Wideband displays: mitigating multiple monitor seams. In: Proceedings of CHI '04. Vienna, Austria, pp. 1521–1524.

McFarlane, D.C., 2002. Comparison of four primary methods for coordinating the interruption of people in human-computer Interaction. Human-Computer Interaction 17 (1), 63–139.

Mynatt, E.D., Igarashi, T., Edwards, W.K., LaMarca, A., 1999. Flatland: new dimensions in office whiteboards. In: Proceedings of CHI '99. pp. 346–353.

Ni, T., Bowman, D., Chen, J., 2006. Increased display size and resolution improve task performance in information-rich virtual environments. Graphics Interface(GI) 2006, 139–146.

Pedersen, E., McCall, K., Moran, T.P., Halasz, F., 1993. Tivoli: an electronic whiteboard for informal workgroup meetings. In: Proceedings of CHI '93. pp. 391–398.

Simmons, T., 2001. What's the optimum computer display size? Ergonomics in Design, 19–25.

Shupp, L., Ball, R., Yost, B., Booker, J., North, C., 2006. Evaluation of viewport size and curvature of large, high- resolution displays. Graphics Interface (GI) 2006, 123–130.

Tan, D., Stefanucci, J.K., Proffitt, D., Pausch, R., 2001. The infocockpit: providing location and place to aid human memory. In: Proceedings of PUI '01. pp. 1–4.

Tan, D.S., Czerwinski, M., November 2003. Effects of visual separation and physical discontinuities when distributing information across multiple displays. In: Proceedings of OZCHI03 (Australian Computer Human Interaction Conference). Brisbane, Australia, pp. 184–191.

Tan, D., Czerwinski, M., Robertson, G., 2003a. Women go with the (optical) flow. In: Proceedings of CHI '03. pp. 209–215.

Tan, D., Gergel, D., Scupelli, P., Pausch, R., April 2003b. With similar visual angles, larger display improve spatial performance. In: Proceedings of HI '03. pp. 217–224.

Tan, D., Gergel, D., Scupelli, P.G., Pausch, R., April 2004. Physically large displays improve path integration in 3d virtual navigation tasks. In: Proceedings of CHI '04. pp. 439–446.

Tse, E., Greenberg, S., Shen, C., Forlines, C., 2006. Multimodal Multiplayer Tabletop Gaming. In: Proceedings Third International Workshop on Pervasive Gaming Applications (PerGames'06).