Increased Display Size and Resolution Improve Task Performance in Information-Rich Virtual Environments

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Figure 1. Apparatus used in our experiment. From left to right: (a) High-resolution IBM™ T221 LCD flat panel, (b) Rear-projected screen, and (c) VisBlocks™ tiled high-resolution display module.

ABSTRACT

Physically large-size high-resolution displays have been widely applied in various fields. There is a lack of research, however, that demonstrates empirically how users benefit from the increased size and resolution afforded by emerging technologies. We designed a controlled experiment to evaluate the individual and combined effects of display size and resolution on task performance in an *Information-Rich Virtual Environment* (IRVE). We also explored how a wayfinding aid would facilitate spatial information acquisition and mental map construction when users worked with various displays. We found that users were most effective at performing IRVE search and comparison tasks on large high-resolution displays. In addition, users working with large displays became less reliant on wayfinding aids to form spatial knowledge. We discuss the impact of these results on the design and presentation of IRVEs, the choice of displays for particular applications, and future work to extend our findings.

CR Categories: H.5.2 [Information Interfaces and Presentation]: User Interfaces – Screen design, Graphical user interfaces; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism – Virtual Reality; J.4 [Social and Behavioral Sciences]: Psychology.

Keywords: Large high-resolution displays, user study, experiment, field of view, wayfinding aid, Information-Rich Virtual Environment (IRVE)

1 INTRODUCTION

With continued advances in display hardware, computational power and rendering algorithms, large high-resolution displays are becoming prevalent in scientific visualization [22], automotive design [7], creativity and innovation [23], and collaboration [14, 16, 17]. A common approach is to couple many commercially available projectors in a *projector array* [18] driven by a PC cluster, producing a tiled seamless large display surface with much higher resolution[1] than a display of the same size produced by a single projector.

A fundamental research question remains: how do users benefit from large high-resolution displays when completing various tasks? Prior research has demonstrated that physically large-format displays improve 3D spatial performance [10, 26, 27]. It has also been shown that large high-resolution tiled displays are beneficial for 2D data visualization, since more details are viewable at once [3]. However, it is still unclear which benefits are due to increased size, which are due to higher resolution, and which are due to the combination of size and resolution.

To address this research question, we conducted a controlled experiment to measure the effects of size and resolution on task performance in an *Information-Rich Virtual Environment* (IRVE). IRVEs combine traditional VEs and Information Visualization, enhancing spatial and perceptual VEs with additional abstract information such as text and graphs [4, 6]. IRVEs are commonly

[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. Therefore, we say that a display with 1600×1200 pixels has a higher resolution than one with 800×600 pixels, regardless of the size or pixel density of the displays.

used for applications such as medical visualization, design, and education, which include abstract information to convey a richer set of knowledge. We chose an IRVE in our experiment because the requirements of IRVEs seem to be a good match for the capabilities of large, high-resolution displays. IRVEs require both 3D spatial navigation, which should benefit from the wide field of view afforded by large displays, and abstract information comprehension (e.g. text reading), which should benefit from high resolution.

In our work, we have isolated display size and resolution as independent variables by using three different display technologies. A high-resolution desktop display (Figure 1a) is small in size and can be used at both low and high resolutions; a single projector (Figure 1b) can provide a large, low-resolution display; and an array of projectors (Figure 1c) produces a large, high-resolution display. Such an experimental design enables us not only to examine these two factors separately, but also to comprehend how they interact with each other.

By replicating and extending prior results, we contribute a deeper understanding of how large high-resolution displays affect task performance in interactive 3D environments incorporating both perceptual and abstract information. Additionally, we show that users working with large displays become less reliant on wayfinding aids to acquire spatial knowledge and construct cognitive map of virtual environments. Our results, combined with existing findings, lend significant insights for the design and presentation of large-format information display systems. Moreover, we propose a generic experimental design for conducting future evaluation relevant to large high-resolution displays.

2 Related Work

2.1 Large High-Resolution Displays

High-resolution wall-sized displays are becoming more common. The Scalable Display Wall at Princeton University [8], the PowerWall at University of Minnesota [22], and the Interactive Wall at Stanford University [16] are just a few examples. Researchers have realized that "when a display exceeds a certain size, it becomes qualitatively different" [24]. Previous efforts have shown benefits of large-format displays for collaboration and social interaction [12, 14, 16, 17, 23].

Meanwhile, several researchers have focused on investigating individual gains and user behavior on physically large displays. Tan *et al* explored the effects of display size on user performance in reading comprehension tasks involving static text, spatial orientation tasks involving static 2D scenes, and path integration tasks involving interactive 3D VEs [26, 27]. They maintained a constant visual angle by adjusting the viewing distance to each of the two displays in their experimental design, so that they produced retinal images of the same size. Since they did not consider resolution as a variable, no significant difference was observed in reading comprehension performance between the two display sizes, regardless of font size. Surprisingly, better performance was found on spatial orientation and navigation tasks when users worked on a physically large display as compared to a small one, although the large display was positioned far away from users. The authors attributed the enhanced performance to a greater sense of presence afforded by the large display, which allowed subjects to use an egocentric rather than an exocentric strategy to perform spatial tasks.

In practice, however, users are likely to stay relatively close when interacting with large displays. In our study, we allowed users to take advantage of the wider field of view afforded by large displays. Also, technological innovations (e.g. the high-resolution IBM T221 LCD flat panel and the VisBlocks tiled high-resolution display, shown in Figure 1a and 1c, respectively) have enabled us to consider resolution as an additional experimental factor.

Czerwinski *et al* explored the benefits of large displays in terms of reducing gender bias in spatial navigation performance in VEs [10]. They reported that a wide field of view coupled with a large display benefits both male and female users and effectively reduces gender bias. Although we did not explicitly consider gender as a variable in our experiment, our experimental results do replicate what prior work has shown.

Ball *et al* [3] described an exploratory study examining the effectiveness of large high-resolution displays on basic low-level data visualization and navigation task performance. They concluded that with finely detailed data, large high-resolution displays result in more physical navigation, which is preferable to virtual zoom and pan on small displays. However, they dealt with a static 2D data visualization in their study, and they did not investigate the individual effects of size and resolution as independent variables.

In summary, there is still a lack of systematic approaches and empirical evidence to demonstrate both the benefits and limitations of large high-resolution displays on a broad range of tasks [20].

2.2 Field of View

There are two *field of view* (FOV) angles to be considered when referring to display characteristics. The (horizontal) *physical field of view* (PFOV) (or display field of view in other literature) is the angle subtended from the eye to the left and right edges of the display screen [10]. Therefore, if a display of 48" in width is placed 24" from a user's eyes, the horizontal PFOV will be 90°. The (horizontal) *software field of view* (SFOV) (or geometric field of view in other literature) is defined as the angle subtended from the virtual camera to the left and right sides of the viewing frustum [10]. Unlike PFOV, which is determined by the physical parameters of a display and the viewing distance, it is the application developer who controls SFOV. It is important to distinguish PFOV from SFOV in an experimental design. Unfortunately, most published literature has confounded these two terms.

The effects of PFOV on VE task performance have been extensively studied [1, 2, 10, 11, 13, 19, 28]. Arthur conducted a comprehensive experiment carried out in head-mounted displays [2], which demonstrated that restricting PFOV degraded human performance on search and locomotion tasks in VE. Alfano and Michel [1] found that a wider PFOV yielded significantly better performance than more restricted PFOVs did on eye-hand coordination tasks. Furthermore, the relationship between PFOV and spatial awareness and memory structure has been explored in [19, 28]. Users developed more spatial awareness as well as a higher sense of presence with a wider PFOV, and exhibited better recall of VEs. A wider PFOV (when combined with an equally wide SFOV) aids many spatial tasks; in particular, the acquisition of spatial knowledge in 3D environments is a task relevant to our work that benefits from a wide PFOV.

Only a few papers (e.g. [10, 21]) explicitly make the distinction between PFOV and SFOV. Czerwinski *et al* [10] examined three PFOV:SFOV ratios via combining narrow and wide SFOVs with small and large display sizes. In our work, we also avoided confounding PFOV and SFOV by maintaining a constant 1:1 PFOV:SFOV ratio.

2.3 Information-Rich Virtual Environments

A working definition of an IRVE is "a realistic VE that is enhanced with the addition of related abstract information" [6].

Polys *et al* reported [21] on the design and evaluation of two information layout techniques in IRVEs. The Object-Space technique places annotations (textual labels) in the world, near to their referent virtual objects, while the Viewport-Space technique displays labels on the image plane. We decided to display Object-Space textual labels in our environment (Figure 2), since they provide depth cues such as occlusion, motion parallax, and linear perspective consistent with referent objects. In addition, they mimic the way we associate annotations with objects in real world environments.

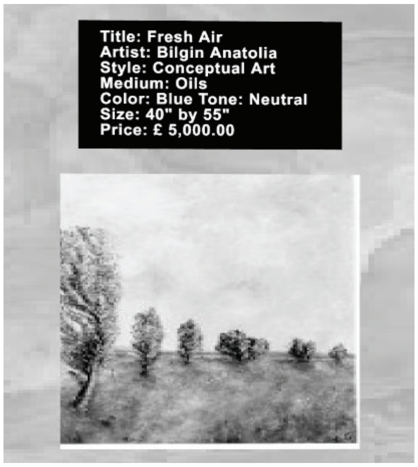


Figure 2: An Object-Space textual label with descriptions of a corresponding painting.

3 Experiment

In our study, we designed a controlled experiment in which we examined display *size* and *resolution* as independent variables. Our goal was to investigate how large high-resolution displays affect task performance in IRVEs. We had the following primary hypothesis:

Hypothesis 1: Increased display size will benefit 3D navigation, and higher resolution will improve the legibility of textual labels. As a result, users will be most effective on IRVE search and comparison tasks when they work with a large high-resolution display.

We also examined the effectiveness of providing wayfinding aids under various display setups. Thus:

Hypothesis 2: Users will be more effective on IRVE tasks when a wayfinding aid is presented, since it facilitates spatial knowledge acquisition and cognitive map construction. However, wayfinding aids will be of less benefit when users work with large displays, since such displays provide a wider field of view and better optical flow cues, enabling efficient and accurate mental map construction.

3.1 Environment

We developed a multi-room art museum using Virtual Reality Modeling Language (VRML). Each room contained paintings and textual labels with descriptions of the paintings. We collected paintings from Art Trader UK (http://arttraderuk.com).

We classified paintings by their *styles*. For instance, Figure 2 shows a painting classified as "*conceptual art*." Other styles include "abstract art", "figurative art", "fantasy art", and so forth. Each museum room was assigned a unique style and was named after that style. Figure 2, then, shows a painting that would be found in the *conceptual art room*. In performing tasks, participants were to search for specific information in one or more rooms whose names were given in the task description.

This virtual world represents a typical IRVE, since it conveys integrated perceptual and abstract information.

3.2 Experimental Design

We adopted a 2 (size) × 2 (resolution) between-subjects experimental design, with eight participants assigned to each experiment condition (Table 1). Females were evenly distributed in each condition to eliminate gender bias. In this paper, we denote the four conditions as *SL* (small-size low-resolution), *SH* (small-size high-resolution), *LL* (large-size low-resolution), and *LH* (large-size high-resolution). We also refer to the first two conditions as the *S-group*, and the latter two as the *L-group*. Task type and the use of a wayfinding aid were within-subjects variables.

Table 1: Experimental design.

	S-group	L-group
	Small-size (42.8° FOV)	**L**arge-size (90° FOV)
Low-resolution (1280×720)	– Map	– Map
	+ Map	+ Map
High-resolution (2560×1440)	– Map	– Map
	+ Map	+ Map

3.2.1 Between-subjects variable: display size

In [26, 27], Tan *et al* maintained a constant visual angle by adjusting the viewing distance to each of two displays. We, however, took a different approach, holding the *viewing distance* constant. Figure 3 illustrates our experiment configuration. The large and small screens were 48.0" and 18.8" in width, respectively. We assumed a comfortable viewing distance of 24.0", and thus achieved a 90º horizontal PFOV for the L-group, and roughly 42.8º for the S-group.

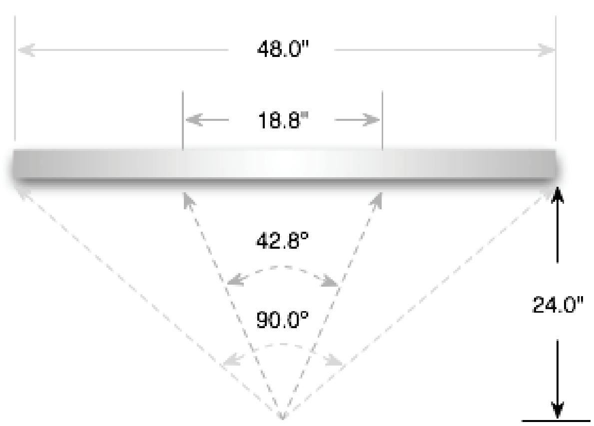


Figure 3: Experiment configuration. We held a constant viewing distance (24.0") across all experiment conditions, resulting in a 90.0º horizontal PFOV for the L-group, and roughly 42.8º for the S-group.

We also used 90º and 42.8º SFOVs with the large and small screens, respectively. It has been reported that deviating from a 1:1 ratio of PFOV to SFOV is harmful, especially for VE navigation [11], since large deviations result in either unrealistic magnification or miniaturization of objects in VEs [10]. The wider field of view cast a larger retinal image and afforded better optical flow cues [25]. As a result, given a viewpoint, subjects in the L-group perceived more information than those in the S-group (Figure 4).

Figure 4: Given the same viewpoint, the 90.0° and 42.8° SFOV angles cause differences in visual perception. The upper image simulates the user's view in the large-size, low-resolution (LL) condition, while the lower image simulates the small-size, low-resolution (SL) condition.

3.2.2 Between-subjects variable: display resolution

Within the S- and L-groups, we used two levels of resolution at 1280×720 and 2560×1440 pixels, respectively. Due to the higher resolution, the legibility of textual labels in the SH and LH conditions was considerably improved, compared to the SL and LL conditions. However, given the same level of resolution, we ensured that textual labels were displayed using the *same number of pixels*. The top image in Figure 4 shows the LL condition (the label appears large relative to the painting), while the lower image shows the SL condition (the label appears smaller, but occupies the same number of pixels). The geometric size of the labels was held constant across resolutions; i.e. labels in the SL and SH conditions appeared to be the same size, and labels in the LL and LH conditions also appeared to be the same size.

3.2.3 Within-subjects variable: wayfinding aid

We were also interested in how a wayfinding aid facilitated spatial knowledge acquisition and cognitive map construction when users worked with various displays. We therefore developed a plan-view map (Figure 6) of the VE as a wayfinding aid. It provided an exocentric representation of an environment and assisted users in forming survey knowledge [5]. Map usage was a within-subjects variable (Table 1).

Under each condition, participants performed two sets of eight tasks. Before each set of tasks, subjects completed a practice session, during which we explicitly instructed them to construct a cognitive map of the VE, focusing on how rooms were organized. To prevent subjects from acquiring any task-relevant knowledge, we reduced the available abstract information in practice sessions, exposing only the name of each room. A virtual compass (Figure 5) conveying directional information was also made available to assist users in developing spatial knowledge during each practice session. Consequently, participants did not execute a naïve search during the actual task sessions, and the possibility of learning effects was reduced. The wayfinding aid (map) was provided in counterbalanced order in *one* of the two practice sessions, in order to see how task performance was affected. Participants were warned that they would not have the map while performing tasks. In addition, we designed two different layouts of the virtual museum, which were used for the two sets of tasks in counter-balanced order, such that the spatial knowledge obtained in one set would not apply in the other (Figure 6).

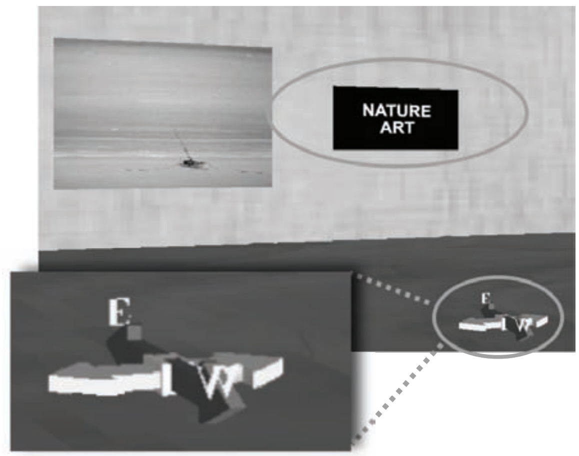


Figure 5: VE in practice sessions with reduced abstract information and a compass.

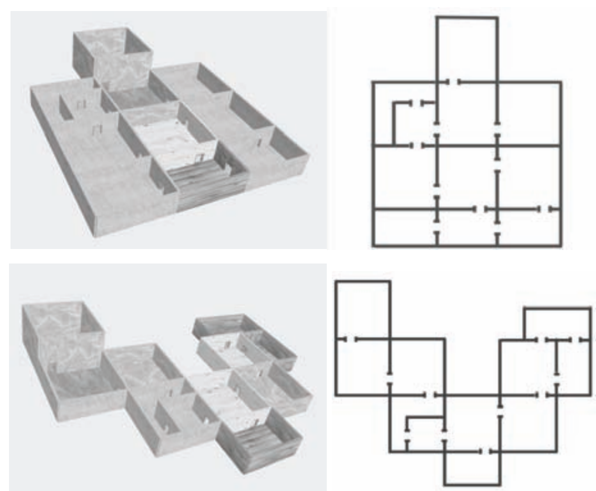


Figure 6: Reorganized virtual environments and corresponding plan-view maps.

3.2.4 Within-subjects variable: task type

Participants performed four types of tasks, representing various conditions a user is likely to experience in an IRVE [9]. Tasks first required navigation to one or more target rooms, and then search and comparison of perceptual and abstract information (i.e. textual labels). We designed two tasks for each type, leading to eight tasks in each set. Participants completed tasks in each set in random order. Table 2 describes each task type with examples.

In summary, our experiment consisted of:

8 participants ×
2 sizes ×
2 resolutions ×
2 task sets ×
4 task types ×
2 tasks ×
= 512 data points

The between-subjects independent variables were size and resolution, and the within-subjects independent variables were wayfinding aid and task type. Task completion time was recorded as a dependent variable. Errors were not possible since we waited for the correct answer before proceeding to the next task.

Table 2: Task types.

1. Abstract information followed by additional related abstract information (A-A). *Example*: In the abstract art room, find the artist of the painting entitled "Paradise".
2. Perceptual information followed by abstract information (P-A). *Example*: To the south of the conceptual art room, find the most expensive painting.
3. Perceptual information followed by additional perceptual information, and then abstract information (P-P-A). *Example*: To the east of the fantasy art room, find the painting depicting a tiger, and then find the tone of the painting.
4. Abstract information followed by perceptual information, and then additional abstract information (A-P-A). *Example*: In the historical art room, find the artist of the most expensive painting, and then to the west of that room, find the medium of the painting by the same artist.

3.3 Apparatus

Throughout our experiment, a PC workstation with an nVidia Quadro FX 3400 graphics card was used, running Windows XP with the Cortona VRML Client 4.2 for VRML rendering. A Dell wireless keyboard was used for VE navigation. Users pressed the up/down arrow keys for moving forward/backward, and the left/right arrow keys for turning.

Figure 1 presents the displays used in the study. In both the SL and SH conditions, an IBM T221 LCD flat panel, which supports resolutions up to 3840×2400, was used (Figure 1a). In our experiment, we set it to 1280×720 and 2560×1440 pixels, respectively (a 16:9 aspect ratio). The display was roughly 18.8" by 10.6". Thus, the SH condition has a pixel density of 136.2 pixels per inch, while the SL condition has a pixel density of 68.1 pixels per inch.

In the LL condition, we used a rear-projected screen powered by a Dell 3300MP DLP projector (Figure 1b). A resolution of 1280×720 pixels was set, and the size of the rendered image was calibrated to 48" by 27". Obviously, this display had the lowest pixel density among our four conditions (26.7 pixels per inch).

In the LH condition, we used the VisBlocks, a reconfigurable tiled high-resolution display module made by VisBox Inc. (Figure 1c). Each block is 24" by 13.5" in size, with a resolution of 1280×720 pixels. In our experiment, we used four blocks arranged in a 2x2 array, which created a screen size of 48" by 27" and a resolution of 2560×1440 pixels. The pixel density of this display (53.3 pixels per inch) was slightly lower than that of the SL condition. To drive the VisBlocks, we used a secondary nVidia GeForce FX5200 PCI graphics card such that we had four video outputs, one for each block.

Across all experiment conditions, we attempted to maintain similar color, brightness and contrast for each display, but there were inevitable differences. In general, the small display has better color, brightness, and contrast. In addition, the four VisBlocks in the LH condition were not perfectly color matched. Due to the limitations of the available graphics hardware, we were unable to achieve a sufficiently high frame rate on the VisBlocks (5-8 fps), as compared with the other equipment (approx. 40 fps). VE navigation was still usable, however, and this limitation did not appear to bother participants.

3.4 Participants

Subjects were recruited on our university campus. 32 subjects (4 females) aged 19 to 32 participated in the study. All subjects had normal or corrected-to-normal vision. Users were intermediate to experienced computer users who played video games less than once per week, according to self-reports.

3.5 Procedures

Upon arrival, participants filled in a background survey form and performed the Map Planning Test (SS-3) from the ETS Kit of Factor-Referenced Cognitive Tests [15], an instrument commonly employed to evaluate spatial ability skills.

Users read an experiment manual with detailed instructions on experiment goals, environments, apparatus and procedures. Participants were seated in front of the assigned display. They then performed two sets of eight tasks, with a practice session before each set, and the time taken for each task was recorded. Participants were allowed to take a break between the two sets, and they were free to stop the experiment if they felt uncomfortable. Finally, they completed a post-experiment questionnaire containing five-point Likert scales regarding their level of difficulty in navigating, the legibility of textual information, their level of reliance on the map, and their usage of screen real estate. Subjects were also welcome to add any comments relevant to their experiences. The entire experiment lasted about 1 to 1.5 hours.

4 Results and Analysis

Since the tasks designed for each set required different amounts of navigation to complete, we normalized the performance data against the *shortest navigation distance* for each task before we performed any statistical analysis. We performed a mixed model analysis of variance (ANOVA) in which display size and resolution were treated as between-subjects variables, and the presence of the wayfinding aid and task type were taken as within-subjects factors.

Scores on the SS-3 subtest were compiled and submitted to a series of Welch's t-tests, assuming unequal variances. No significant between-groups difference was observed, ensuring the validity of our subsequent analysis.

4.1 Overall Performance

Figure 7 illustrates the overall results of our experiment with respect to normalized average task completion time. It is clear that the LH condition resulted in the best task performance, while the SL condition was the worst. Even subjects working with a high resolution on a small screen did not outperform those on a large display with many fewer pixels. Therefore, participants in the L-group were more effective in executing IRVE tasks than those in the S-group. Our primary ANOVA (*alpha-level* = 0.05) found statistically significant main effects of both *size* ($F(1,192) = 39.86$, $p < 0.0001$) and *resolution* ($F(1,192) = 8.78$, $p = 0.0034$), which conformed to our first hypothesis. The interaction between size and resolution was not statistically significant ($F(1,192) = 0.72$, $p = 0.3958$).

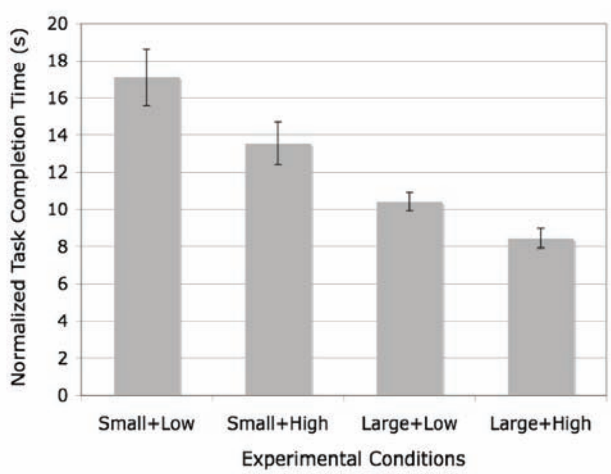


Figure 7. Overall average task performance revealed main effects of display size and resolution. Error bars show standard errors.

An interesting finding, visible in Figure 7, is that the variance in the LL and LH conditions was much smaller than that in the SL and SH conditions. This indicates that users had more stable task performance on large displays. We believe this is because the large displays improved navigation performance and hence reduced individual differences in spatial ability.

Participants in the SH condition performed about 26.35% better than those in the SL condition (13.55s vs. 17.12s), and participants in the LH condition performed about 23.31% better than those in the LL condition (8.45s vs. 10.42s). However, it is interesting to note that within the S-group, we only observed a marginally significant effect of resolution ($F(1,96) = 4.13$, $p = 0.0448$), while within the L-group, a strong main effect of resolution was found ($F(1,96) = 9.31$, $p = 0.0029$). This suggests that users working with large displays benefit more from a higher resolution. This is a reasonable result, since large display users could see more of the environment, and therefore more labels, at once. The high resolution allowed these labels to be legible even from a large distance.

Not surprisingly, we also found a significant main effect of *task type* ($F(3, 192) = 22.74$, $p < 0.0001$) on completion time, since the task types differed in level of difficulty and amount of cognitive activity involved. However, we did not observe any interaction between task type and the other independent variables, indicating that the benefits of increased size and resolution hold up across a variety of tasks.

4.2 Effects of Wayfinding Aid

In general, when users were presented a map in the practice session, they performed more effectively regardless of the display condition (Figure 8). Our statistical analysis revealed a significant main effect of *wayfinding aid* ($F(1,192) = 9.73$, $p = 0.0021$). After receiving the wayfinding aid, subjects in the SL condition completed tasks about 40.54% faster (14.23s vs. 20.00s); and those in the SH condition finished tasks about 46.86% faster (10.98s vs. 16.13s). In both the LL and LH conditions, subjects performed slightly better when the wayfinding aid was available. A post-hoc ANOVA revealed a significant main effect of wayfinding aid in the SL ($F(1,14) = 6.28$, $p = 0.0252$) and SH ($F(1,14) = 6.92$, $p = 0.0197$) conditions, but not in the LL ($F(1,14) = 0.10$, $p = 0.7561$) and LH ($F(1,14) = 0.15$, $p = 0.7045$) conditions. We also observed a statistically significant interaction (Figure 9) between *wayfinding aid* and *size* ($F(1,192) = 7.40$, $p = 0.0071$), again demonstrating that the effect of the wayfinding aid on completion time was much stronger with the small displays.

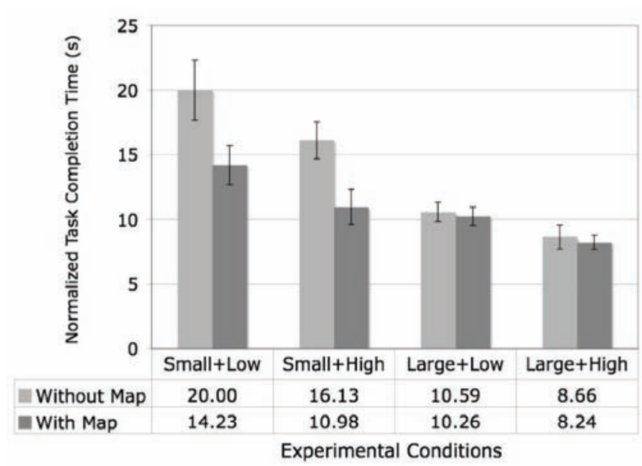


Figure 8. Effects of wayfinding aid on task performance. Error bars show standard errors.

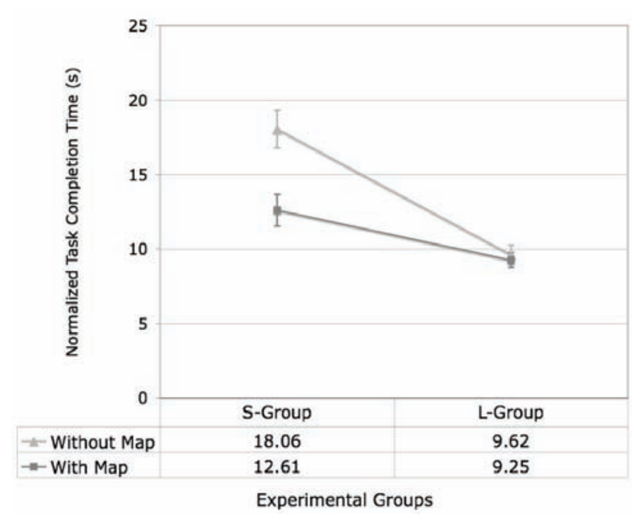


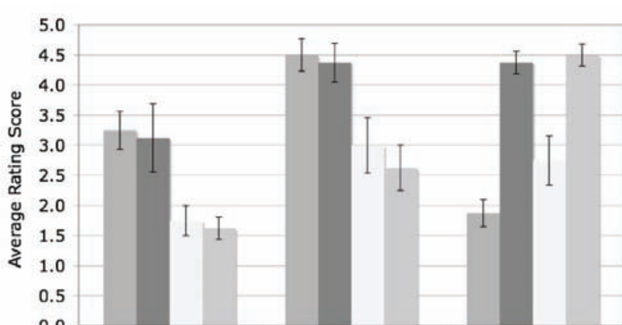
Figure 9. Interaction between wayfinding aid and size is significant.

These results were consistent with our second research hypothesis. Wayfinding aids such as a map are helpful for spatial knowledge acquisition and cognitive map construction in navigating a VE. However, only when users worked with relatively small displays was this effect significant. In our experiment, the large displays provided a wider PFOV and SFOV, leading to better optical flow cues, which in turn facilitated spatial knowledge acquisition and cognitive map construction. Consequently, the negative effect of lacking the wayfinding aid was greatly mitigated.

4.3 Subjective Ratings

The average subject ratings with respect to level of difficulty in *navigation* (1: least difficult, 5: most difficult), level of reliance on *wayfinding aid* (1: least useful, 5: most useful), and *legibility* of textual information (1: least readable, 5: most readable) are illustrated in Figure 10.

A two-way ANOVA found a significant main effect of *size* on average *navigation* score ($F(1,15) = 20.77$, $p = 0.0004$) and *wayfinding aid* score ($F(1,15) = 35.70$, $p < 0.0001$), indicating that subjects perceived more difficulty in navigation and became more reliant on the wayfinding aid when they worked with small displays. A significant main effect of *resolution* on average *legibility* score was also observed ($F(1,15) = 45.63$, $p < 0.0001$). These findings clearly support our analysis of task performance.



	Navigation	Wayfinding Aid	Legibility
SL	3.25	4.50	1.88
SH	3.13	4.38	4.38
LL	1.75	3.00	2.75
LH	1.63	2.63	4.50

Figure 10: Subjective rating scores. Error bars show standard errors.

4.4 User Behavior

We also observed users' behavior when they performed tasks on large displays. In particular, we were interested in examining whether or not they tended to utilize the full screen, rather than merely focusing on the central area. We found that participants did move their heads frequently and made use of peripheral vision on large displays. Several even tried to see more information by leaning forward, although there was no head tracking in our experiment. Our observations indicated that users felt more present when experiencing large displays, especially when they were seated close to the screen.

5 Discussion and Future Work

Our study provides strong evidence that users are most effective on navigation, search, and comparison tasks in IRVEs when using large high-resolution displays. Our findings demonstrate the advantages of increased size and resolution, contributing a deeper understanding of how we benefit from such displays. As a general guideline, a large high-resolution display is the preferred choice for IRVE applications, since it facilitates both spatial navigation and information gathering.

However, if installing a large high-resolution display is impossible, we have to consider design alternatives more carefully. In our experiment, even a large rear-projected screen outperformed a regular-sized monitor with a higher resolution. Compared to small screens, large displays coupled with a wide SFOV are better for IRVEs, even though the text is less legible. In other words, size appears to dominate resolution for IRVE tasks, because task completion time is more dependent on efficient navigation than on text legibility.

However, this begs a question: how will IRVE performance be affected by PFOV:SFOV ratios other than one? We held the PFOV:SFOV ratio constant in our experiment for the sake of control, but future work should examine the use of other ratios (e.g. a wider SFOV on a small display), in order to investigate which FOV plays a dominant role in contributing better spatial navigation performance. In fact, many desktop 3D applications use wide SFOVs as the default without apparent loss of usability.

We found an interaction between wayfinding aid and display size. Although we presented the map only in the practice session (users were not permitted to use it while performing tasks), it did improve navigation performance significantly on small displays. Therefore, if large displays are not available, VE designers should consider using wayfinding aids to better support spatial knowledge acquisition. However, the virtual world we presented was not a large-scale complex environment, and the map in our experiment was not a sophisticated wayfinding aid. In future work, it will be interesting to explore other aspects of wayfinding aids and their possible interaction with large high-resolution displays. For example, which wayfinding aids will result in better task performance on semi-immersive large displays, as opposed to immersive virtual environment systems (e.g. Head Mounted Displays and CAVE)? How will wayfinding aids support spatial knowledge transfer from VEs presented on large-format displays to the real world?

There are several other promising avenues for future research. First, we should examine even higher levels of size and resolution, which raises a challenging research question regarding visual scalability. Is there an upper bound beyond which users will be overwhelmed by the displayed information? Second, with the advent of ultra-high-resolution desktop displays, we would like to study the trade-off between the amount of presented information and the legibility of rendered information. That is, we should investigate perceptually valid ways of presenting information on new displays. Third, since it is also possible to reconfigure certain high-resolution displays, we plan to experiment with various display form factors, such as planar, faceted, or curved displays. Finally, our basic experimental design is generalizable, and we will reuse it to study other applications proposed for large high-resolution displays. This design allows us to evaluate the effects of size and resolution independently, but will also show us an interaction between these two variables, if present.

6 Conclusion

We have presented a controlled experiment to evaluate the effects of increased display size and resolution on task performance in IRVEs. A factorial experimental design approach was adopted in which display size and resolution were treated separately and altered at two levels. Our results replicate and extend prior insights into benefits of large displays in improving spatial VE navigation performance. In fact, we have shown that users working with large high-resolution displays were most effective in performing various navigation, search and comparison tasks. We therefore conclude that the increased display size and resolution reliably improve task performance in IRVEs. However, we recognize that even more empirical evidence demonstrating both the benefits and limitations of large high-resolution displays (or small high-resolution displays) is still necessary.

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