Virtual Reality: How Much Immersion Is Enough?

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Solid evidence of virtual reality's benefits has graduated from impressive visual demonstrations to producing results in practical applications. Further, a realistic experience is no longer immersion's sole asset. Empirical studies show that various components of immersion provide other benefits—full immersion is not always necessary.

In the 1990s, working in the field of virtual reality was cool—VR promised to be the next big thing. Its researchers were besieged with media requests, and futuristic VR systems emerged in popular culture, from Hollywood movies to science fiction novels to TV sitcoms.

Much of the excitement centered on *immersive VR*—complex technologies that replaced real-world sensory information with synthetic stimuli such as 3D visual imagery, spatialized sound, and force or tactile feedback. The goal of immersive virtual environments (VEs) was to let the user experience a computer-generated world as if it were real—producing a sense of presence, or "being there," in the user's mind.

INITIAL VR ADVANTAGES

To a large degree, VR researchers have succeeded in achieving this goal. To be sure, VR technologies—including 3D visual, auditory, and haptic displays; position tracking systems; and input devices—still have usability and fidelity issues. Demonstrations of high-end VR facilities clearly show, however, that immersive VR works.

Users react strongly when first experiencing immersive VR. Seeing the stereoscopic graphics pop out of the screen, picking up a virtual object with their real hand, and realizing that head movements change their view of the virtual world all provide a unique experience. Users comment that immersive VR offers a different experience than interacting with 3D applications on desktop PCs or gaming consoles. Studies such as those that Michael Meehan and colleagues conducted confirm that users do behave and feel differently in immersive VEs.[1]

Clearly, immersive VR is special and unique, but practitioners are using relatively few examples of immersive VR systems in the real world. What measurable benefits can immersion provide? High-end VR technologies, such as head-mounted displays, multiscreen stereoscopic projection displays, 3D tracking systems, and advanced input devices are still quite expensive. If all that these technologies provide for the user are oohs and ahs and a unique user experience, it would be difficult to justify the expense and development complexity that immersive VR requires.

SUCCESS STORIES

In a well-known 1999 article,[2] Fred Brooks posed a related question: What's real about virtual reality? Developers have created successful applications of immersive VR, although the number of *production applications*—Brooks' term for real-world systems used frequently for the results they provide—is limited. Analyzing these applications might provide a better understanding of the known benefits of immersive VEs.

Phobia therapy

As Figure 1 shows, the concept of VR phobia therapy is simple. If a therapist can successfully treat a patient with excessive fear by exposing that individual to the fearful situation in the real world, perhaps virtual exposure will also work. For example, placing a patient with

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a fear of public speaking in a virtual conference room might trigger the same fear structures in the person's brain as actually being there in reality, giving the therapist an opportunity to help bring the fear to a manageable and reasonable level.

Moreover, VR therapy can be less expensive, time-consuming, risky, and embarrassing. By any measure, VR phobia therapy has been a great success. Not only have clinical trials demonstrated its effectiveness,[3] but therapists also use it regularly in real therapy sessions.

Military training

Military training provided one of the first applications of immersive VR.[4] For example, the military can train infantry in urban combat tactics by moving them through a virtual city filled with computer-generated enemies and friendly troops. Training in a virtual world is a good compromise between the traditional alternatives of classroom-based training and real-world training exercises.

VR training provides a level of realism not possible in the classroom, as well as higher flexibility and reduced cost compared to real-world exercises. Recently, the success of VR military training has led to the adoption of VR technologies for other types of training—in the medical field in particular.

Entertainment

Immersive VR has also seen some success in the entertainment industry, although it has been more limited than some predicted. Immersive VR attractions such as those at DisneyQuest[5] place visitors inside the game world even more compellingly than do first-person games on desktop PCs and console gaming systems. While the experience can be impressive, immersive gaming has been limited to a few installations and short gameplay times per user due to the systems' high cost.

SECRETS OF THEIR SUCCESS

Why are these applications successful? They all fulfill requirements in their respective domains and improve on alternatives for meeting those same requirements in some way. But how does immersive VR make a good match for these applications?

One answer is that they all rely on the realistic experience that immersive VEs provide to the user. Specifically, they require a high level of sensory fidelity—visual, auditory, and other sensory cues similar to those experienced in the real world. They require the user's experience in the virtual world to match, as closely as possible, the simulated real-world experience.

In using VR for phobia therapy, the goal is to trigger the brain's fear structures so that the therapist can help the patient manage fear. Assuming that the patient's perceived sensory stimuli activate fear structures, the VR system must produce sufficiently realistic sensory stimuli to trigger fear. Anecdotal evidence suggests that realistic auditory and haptic stimuli might be more important than realistic visuals for some types of phobia therapy.[2]

Figure 1. Virtual conference room used to treat fear of public speaking. (Used with permission, Virtually Better, LLC.)

In military or medical training, the goal is to produce training transfer, that is, to cause the trainee to do the right thing when faced with situations in the real world. This goal is the proper mapping between the sensory stimuli and the appropriate response. It makes sense, then, that training will only be as effective as the training system's sensory stimuli are realistic.

VR gaming applications are slightly different. They aim to engage and entertain the user by producing an experience that's usually impossible to achieve in the real world. Still, VR games achieve this by providing additional sensory cues not available in most gaming systems. For example, Disney's Pirates of the Caribbean attraction[5] uses a wraparound screen with stereoscopic 3D graphics; a physical ship mockup with wheels and cannons the user can touch, turn, and fire; and even simulation of the ship's motion on the waves.

Compared to console gaming, gaming in immersive VR is effective because it provides a more realistic experience, even though the virtual world may not simulate an actual real-world location.

Thus, many successful applications of immersive VR depend on high-fidelity sensory stimuli with the goal of producing a realistic experience that effectively places the user *in* the simulated environment. In other words, these applications require a high level of *immersion* because they produce a sense of *presence*. The "Immersion and Presence" sidebar further describes this concept.

OTHER VR BENEFITS

The VR community has been stuck, so to speak, at this point for many years. As Figure 2a shows, we know that high levels of immersion can cause an increased sense of presence, or a more realistic experi-

Immersion and Presence

Even practitioners familiar with VR are often confused by, or interchangeably use, the terms *immersion* and *presence*, which represent distinct concepts. Mel Slater defines the terms this way:[1]

- Immersion refers to the objective level of sensory fidelity a VR system provides.
- Presence refers to a user's subjective psychological response to a VR system.

A VR system's level of immersion depends only on the system's rendering software and display technology (including all types of sensory displays). Immersion is objective and measurable—one system can have a higher level of immersion than another.

Presence, on the other hand, is an individual and context-dependent user response, related to the experience of "being there." Different users can experience different levels of presence with the same VR system, and a single user might experience different levels of presence with the same system at different times, depending on state of mind, recent history, and other factors.

While many researchers are studying the psychological phenomenon we call presence, we take the more practical approach of studying immersion's effects since we can measure and control its level, and because this approach could have a large real-world impact.

Consider the level of visual immersion—how close the system's visual output is to real-world visual stimuli. Even though visual immersion is only one part of the overall level of immersion, this factor has many components, including

- field of view (FOV)—the size of the visual field (in degrees of visual angle) that can be viewed instantaneously,
- field of regard (FOR)—the total size of the visual field (in degrees of visual angle) surrounding the user,
- display size,
- display resolution,
- stereoscopy—the display of different images to each eye to provide an additional depth cue,
- head-based rendering—the display of images based on the physical position and orientation of the user's head (produced by head tracking),
- realism of lighting,
- frame rate, and
- refresh rate.

Although not exhaustive, this list shows that both hardware and software can play a role in determining the level of immersion. We do not, however, include the realism of the displayed model, as it would be difficult to measure, depend on the specific application running on the hardware and software, and not apply to VEs not based on the real world—such as abstract information visualizations.

We also exclude interaction techniques from our definition of immersion—a more realistic method of interacting with the environment does not raise the level of immersion. Figure A shows the human-VE interaction loop, and indicates the parts of the loop we consider to be components of immersion. Looked at another way, immersion relates to the *view* components in a model-view-controller architecture.

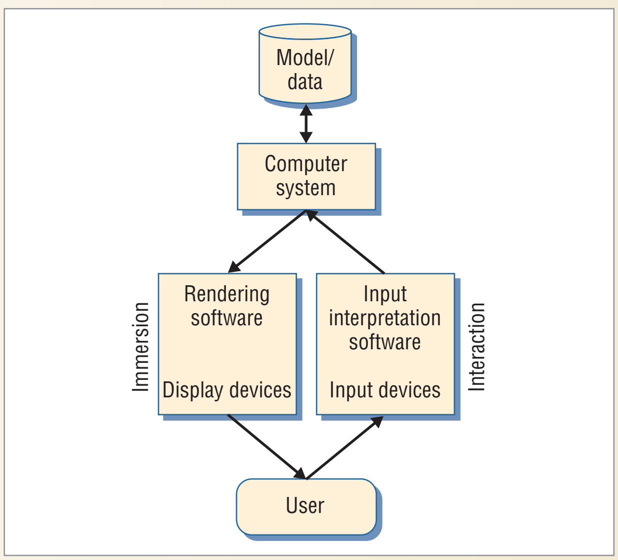

Figure A. Human-VE interaction loop. The components of immersion are limited to display software and hardware.

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1. M. Slater, "A Note on Presence Terminology," *Presence-Connect*, Jan. 2003; http://presence.cs.ucl.ac.uk/presenceconnect/articles/Jan2003/melslaterJan27200391557/melslaterJan27200391557.html.

ence, which can make some applications more effective. But how else can we apply immersive VR technology? The number of applications that would benefit greatly from the realistic experience of a virtual world seems limited. Have we already discovered most successful VR applications? Is immersive VR mostly a gimmick that makes for great demonstrations but offers very little of actual use?

Figure 2b illustrates two complementary strategies for answering these questions. First, presence might not be immersion's only benefit: Applications can take advantage of other side effects of high levels of immersion. Second, we should not consider immersion as a single construct, but rather as the combination of many components, any or all of which can benefit the application. Immersion is not all or nothing, as the terms immersive and nonimmersive suggest, but rather a multidimensional continuum.

To illustrate these concepts, consider how the oil and gas industry has invested heavily in immersive VR systems, using multiscreen stereoscopic immersive projection technologies (IPTs) to visualize and plan underground oil well paths. Users of these systems must be able to view and understand complex 3D structures to make correct decisions.

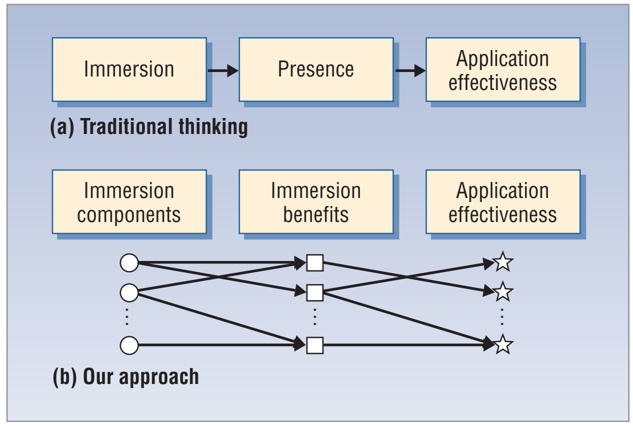

Figure 2. Benefits of immersion. The (a) traditional strategy contrasts with (b) our multidimensional approach.

Such applications provide a simulated view of the real world without requiring presence. The feeling of being there does not help the user perform a task more effectively. In addition, the visualization might even be purposefully abstract, or unrealistic, to help the user better understand the space's critical features.

Kenny Gruchalla performed a user study[6] comparing desktop- and IPT-based versions of an oil well path-planning application, as Figure 3 shows. He found that the IPT version of the system resulted in significantly higher performance. Higher levels of immersion in this application clearly produced a measurable benefit aside from mere presence. In this case, the benefit was probably increased spatial understanding, although Gruchalla did not measure this directly. The "Potential Benefits of Immersion" sidebar describes other possible benefits of immersion beyond the sense of presence.

But why did this benefit occur? Is it because the IPT-based system had larger screens or a wider field of view (FOV)? Did head tracking enable physical exploration of the space? From this experiment, we cannot tell which components of immersion produced the benefit. Perhaps all the components present in the IPT-based system were necessary, which would mean that an equivalent system would be required to realize the benefits. But it's equally likely that only one of the immersive technologies, such as head tracking, resulted in the improved performance. If this were the case, a much simpler Fishtank VR system (head-tracked stereo graphics with a standard monitor) would be sufficient.

Potential Benefits of Immersion

While it provides a realistic experience that enables applications like training and phobia therapy, we believe immersion can potentially offer many other benefits as well.

The most intuitive of these additional benefits is *spatial understanding*. In the real world, we perceive a stable, 3D environment, even though our eyes only sense 2D projections of that environment. The human brain is highly optimized for reconstructing 3D scenes from these images by exploiting depth cues such as stereopsis, motion parallax, perspective, and occlusion.

Immersive VR provides many depth cues that other technologies do not; in particular, stereo images and head tracking let users exercise their built-in capacity for understanding stereopsis and motion parallax. It should not be surprising, then, that a higher level of immersion can lead to greater spatial understanding, which can result in greater effectiveness for many applications such as scientific visualization, design review, and virtual prototyping.

Another potential benefit of immersion relates to a decrease in *information clutter*. We are all familiar with computer desktops littered with overlapping icons, windows, controls, and notifications. Some researchers are trying to address this problem with virtual desktops, or, better yet, multiple physical monitors.

In VR, we experience an analogous problem when we add information to our virtual worlds and visualizations—text, numbers, glyphs, and such clutter the 3D scene. With a higher level of immersion, however, we might be able to decrease this clutter and increase the environment's comprehensibility. Specifically, increased FOV, FOR, and display resolution could have this effect.

These and other potential benefits of immersion—such as increased *peripheral awareness* or increased useful *information bandwidth*—have largely gone untested until now. Demonstrating these benefits could open the door for many other viable applications of immersive VR.

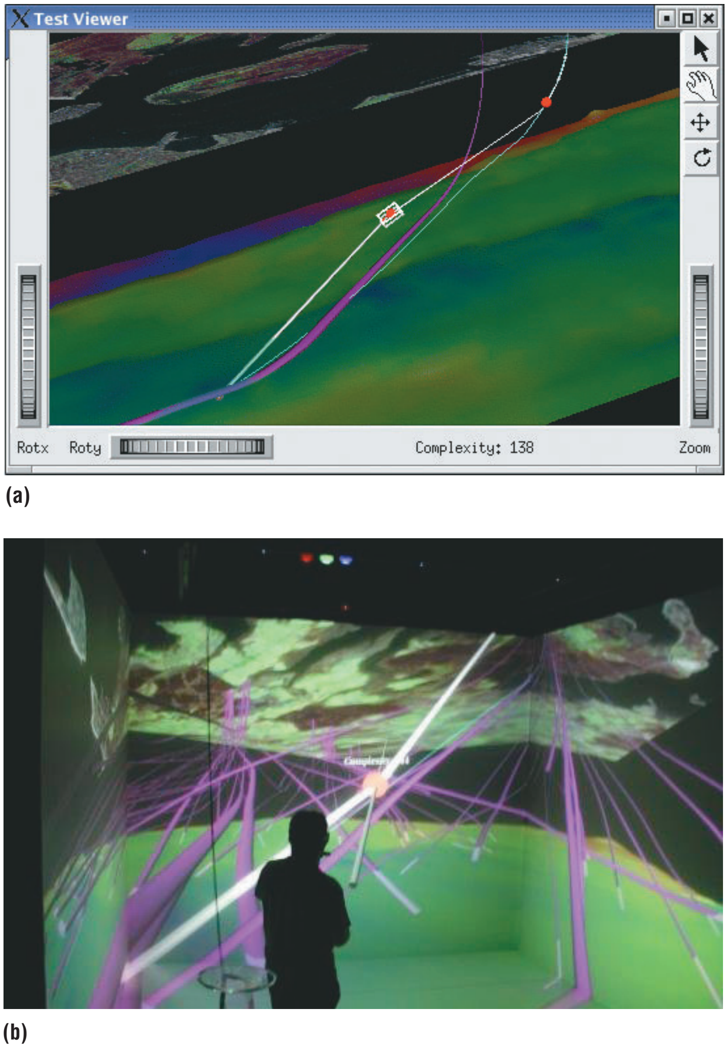

Figure 3. (a) Desktop and (b) immersive versions of Gruchalla's oil well path-planning application. (Used with permission, Proc. IEEE Virtual Reality.[6])

To address concerns such as these, the VR community runs controlled empirical studies, usually to investigate a single component of immersion's effect on task performance. For example, researchers might study the effect of increasing display resolution on the amount of time to complete a visual search task.

Because everything except the component of interest is held constant, the results of these studies offer high generality. On the other hand, the choice of constant levels for other factors can significantly impact results. For example, studying the effect of display resolution on a small, nonstereo, nonhead-tracked display might produce very different results than studying the effect of resolution in a head-mounted display. In addition, such single-factor studies don't capture the richness of the difference between systems that we think of as immersive and nonimmersive.

Taking a two-step approach to address these limitations, we first run a more practical study, similar to Gruchalla's, with a drastic difference in the levels of immersion. If this is successful, we then investigate multiple components of immersion simultaneously with multiple levels per component, while still maintaining a high degree of experimental control. This lets us study not only single components' effects, but also the interaction between components. This also lets us simulate real-world systems in a controlled way by combining immersion components differently.

As an example, civil engineers can use the AMADEUS visualization system shown in Figure 4 to model and analyze the internal structure of rock masses to determine an appropriate design for an underground space, such as a tunnel. The visualization is 3D, complex, and difficult to comprehend, since it doesn't resemble anything the engineers are accustomed to viewing in the real world.

Because of these characteristics, AMADEUS users might benefit from a more immersive system. We built the application using a software toolkit that can display the visualization on a desktop PC, CAVE (a specific type of IPT), or anything in between. Our civil engineering collaborators, in particular, built a small single-screen nonhead-tracked stereo display, referred to as a GeoWall, with the idea that it might represent a good compromise between the desktop and the CAVE.

Our approach to evaluating the effects of immersion in AMADEUS follows the two-step process. First, we compare users' task performance (speed and accuracy) on low-immersion and high-immersion systems. To

DEMONSTRATING IMMERSION'S BENEFITS

Gruchalla's study takes an important first step toward realizing additional, and more effective, immersive VR applications—demonstrating empirically that an immersive system is significantly better than a nonimmersive system for a particular task. Such results are critical for applying immersive VR applications beyond traditional categories like therapy, training, and entertainment. However, studies like this are limited in their generality and explanatory power. Many questions remain, including

- what other tasks or applications might realize similar benefits,
- which components of immersion result in benefits, and
- whether a lower level of immersion can yield the same benefit.

maintain some level of control, we use the CAVE hardware to implement both of these systems rather than directly compare the real-world systems. The high-immersion condition uses the CAVE's full capabilities, but we use only a single screen—without stereo and head tracking—to produce a low-immersion condition similar to both the desktop PC and the GeoWall. Table 1 shows the level of selected immersion components for the three real-world systems and our study's two experimental systems.

If this first experiment demonstrates a significant difference between the low- and high-immersion conditions, we run a study in which we independently vary stereoscopy, head tracking, and field of regard (FOR). We will continue to use the CAVE hardware to allow independent control of each of these immersion components. We can use the results of this second experiment to develop a model that can predict users' performance on these tasks with a wide range of real-world systems.

RESULTS

Since 2004, we have performed more than a dozen experiments on the benefits of immersion using this basic methodology. The catalyst for our work in this area was our research on VR-based information visualization. We felt certain that in some visualization tasks, a more immersive system would result in improved task efficiency, higher levels of accuracy, and greater overall understanding of the data set, but we were not sure how to evaluate that claim.

An early experiment comparing a tracked head-mounted display to a desktop PC for 3D information visualization was promising, but it had too many confounds to let us state with confidence that immersion improved performance. When we began to design a more controlled experiment, we found that the CAVE was a more suitable platform because we could control FOR and head tracking independently, which is not possible with head-mounted displays. It also provided a much broader potential range of screen sizes, resolutions, and FOVs.

Since then, we have studied the effects of

- FOR and stereoscopy on single-user object manipulation[7];
- stereoscopy and head tracking on collaborative object manipulation[8];
- display size and resolution on search tasks[9];
- display size and software FOV on search and comparison tasks[10];
- stereoscopy, FOR, and head tracking on spatial understanding[11]; and
- reduced visual distraction on spatial understanding and memory.[12]

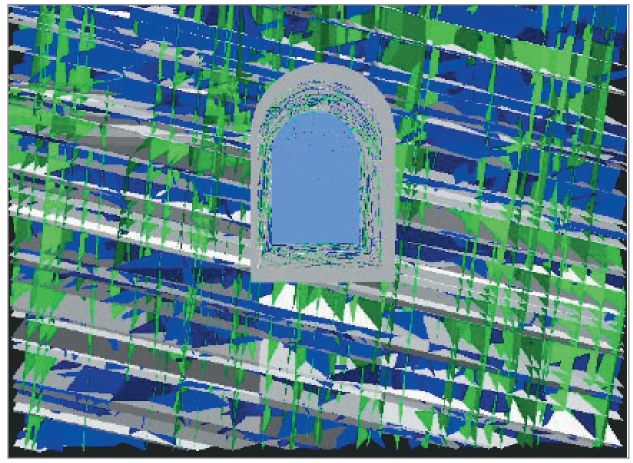

Figure 4. Visualization of tunnel through rock fractures in AMADEUS.

We have far to go before completely understanding the benefits of immersion and the components that produce them. While we will embark on a major effort to more systematically cover the experimental space, we can draw several preliminary conclusions now.

First, several of our studies have found positive effects of immersion on spatial understanding. In particular, stereoscopy, head tracking, and wide FOR appear to work together to provide this benefit. This particular combination of immersive components, found in IPT systems, lets a virtual object or scene be brought inside the physical workspace so that the user can walk around it and see it from every angle, similar to a physical mockup.

For example, in an experiment that currently is under review examining immersion's benefits for visualization of underground cave structures, both speed and accuracy significantly improved when expert spelunkers answered questions about spatial relationships, paths, and proximity in a highly immersive system with stereo, head tracking, and wide FOR. Task performance was two to three times faster in the high-immersion condition, and question responses were three to 10 times more accurate.

Table 1. Levels of selected immersion components for real-world and experimental VR systems.

System	Field of regard	Stereoscopy	Head tracking
Real world			
Desktop PC	~20 degrees	No	No
GeoWall	~60 degrees	Yes	No
CAVE	~270 degrees	Yes	Yes
Experimental			
Low-immersion	90 degrees	No	No
High-immersion	270 degrees	Yes	Yes

This effect, however, does not always hold. In the same experiment, we saw no difference between the two conditions for simpler tasks, such as determining the highest point in the cave. There were also some tasks, such as determining a stream's dip angle, that subjects could not perform accurately in either condition.

In visualizations that are less complex, more regular, and easier to understand, less immersive systems might perform as well as the more immersive ones. In a controlled study of abstract information visualizations, for example, we found no significant effects of FOR, stereoscopy, or head-based rendering on many tasks involving 3D scatter plots and surface plots.[13]

Second, we have also found that higher levels of immersion, particularly stereoscopy, can contribute to improved interaction task performance. For example, pairs of users in another experiment performed a manipulation task in which one user controlled an object's position and the other controlled a different object's orientation.[8] Accuracy was measured by counting the number of times the two objects collided, requiring users to be accurate throughout the task.

Users with stereoscopic displays performed this task two times more quickly and made eight times fewer errors, but the use of head tracking had no effect. Since stereopsis is most effective at close range, this result was likely due to the task's required accuracy and the proximity of the object to the user. We can think of this improved interaction performance as another form of improved spatial understanding because the user must be able to perceive the 3D scene accurately to perform the task effectively.

Similar to the previous conclusion, however, this benefit is not found in less complex situations. We conducted another experiment in which individual users performed an object manipulation task at a greater distance.[7] In this case, neither stereoscopy nor FOR had any effect, but the interaction technique was highly significant. The task in this experiment required less spatial understanding because it was performed by a single user and because the task only required the users to place the object in a precise location—we did not measure collisions between objects. Therefore, users were free to experiment with the object's position and orientation until they found the correct location.

Finally, we have evidence that higher levels of immersion can reduce information clutter. In a study on information-rich virtual environments—where 3D spatial information is enhanced with related abstract information such as text—we investigated the effects of display size (with larger displays resulting in a larger FOV) and resolution (number of pixels).[9] The tasks in the study involved searching for a particular piece of spatial information or abstract information or comparing between pieces of information.

We found that both display size and resolution had a significant effect on task completion time, with a large, high-resolution display producing the best results. We believe that the large displays with wide FOVs facilitated navigation and way-finding in the environment, keeping users from becoming disoriented, while the high-resolution displays allowed users to read text annotations from a greater distance, decreasing search time. The combination of wide FOV and high resolution provides a less cluttered, more comprehensible VE.

We have several key goals as we continue our work. Scientifically, we want to understand how the various components of immersion affect measurable user performance, understanding, and preference in a wide variety of VEs. Interactions between components are especially noteworthy; for example, while using stereoscopy and wide FOV individually might not yield any benefits, applying the two together might.

Practically, we have two seemingly conflicting goals. On the one hand, we want immersive VR to succeed and thrive, so we are identifying as many potential benefits of immersion as we can. On the other hand, we would like to help others avoid costly or wasteful situations in which a highly immersive system is not necessary, so we want to find the lowest levels of immersion to realize the benefits. Why use a CAVE when a small stereo wall works just as well?

Perhaps these two goals are not so different. Focusing on traditional immersive VR using high-end IPTs, head-mounted displays, and tracking systems requires demonstrating significant advantages of these systems due to their high cost of entry. But if we relax our definition of immersive and instead concentrate on the continuum of immersion, we can demonstrate the benefits of more practical systems and ultimately attract more applications and users. There is already a trend toward lower-cost, off-the-shelf VR systems, and we predict it will continue as we understand more about immersion's benefits. ■

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