

The Effect of Gaps Between Displays on Spatial Perception and Cognition Tasks in Virtual Environments

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Abstract—We propose the concept of **Gap Between Displays (GBD)** as a component of immersion in virtual environment systems. We hypothesized that GBD may reduce users' task performance in some cases, and choosing appropriate stimuli in GBD can alleviate its negative effects. We performed two empirical experiments to test the two hypotheses. Using a four-screen CAVE™ as the experiment platform, we carefully designed three tasks that cause different levels of awareness of GBD. Using these tasks, we compared users' performance and preference in three conditions. The low-stimulus GBD condition was created by hanging a black cloth across the missing back wall of a CAVE. The high-stimulus GBD condition was created by projected animations and real human motion outside the CAVE. The no-GBD condition was created by a normal usage of the front CAVE wall. The experiment results confirmed our hypotheses and showed that keeping some level of real world distraction may sometimes be better than no distraction at all.

Keywords—Immersive virtual environments, distraction, low-stimulus area, user performance

1 INTRODUCTION

In [18], Slater et al. defined “immersion” as the objective level of fidelity of the sensory stimuli produced by a technological system. So far the VE community has identified many components of immersion, e.g. field of view (FOV), field of regard (FOR), display resolution, stereo, rendering quality and model detail. Since several components of immersion can be effectively controlled, previous research has quantitatively measured the effect of these components on user task performance and users' feeling of presence [10, 13, 21, 23].

A visual display device's FOR is defined as “the amount of the physical space surrounding the user in which visual images are displayed” [1]. Another word, FOR is the total amount visual angle that a user can see when they turn around. Through the usage of a four-screen CAVE™ system and a tiled large display system with bezels, we noticed that one immersion component, the gap between displays, may affect user performance, but cannot be covered by the concept of FOR defined in [1]. We define the *gap between displays* (GBD) as an area that does not show the virtual world, and lies between multiple displays that show the

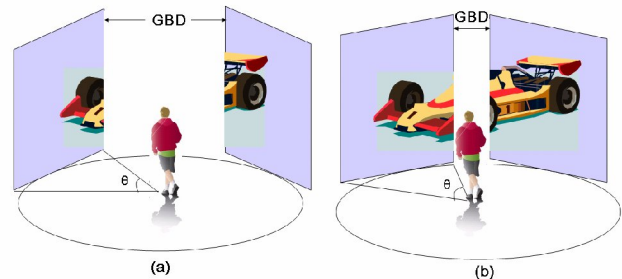


Fig. 1. Gaps between displays (GBD) example. A user in a VE with two displays. The two displays show one connected scene. The FOR in (a) and (b) are both $2 \times \theta$. The GBD in (a) is larger than that in (b).

virtual world. As illustrated in Fig. 1, given a fixed FOR, we can still vary the size of the gap between the two displays or the real world stimuli in the gap. The open back wall on a four-screen CAVE is an example of GBD. We can vary the strength of the real world stimuli in the GBD without changing the FOR.

We lose several aspects of information when GBD exists:

- 1) visual cues about the size of this gap in virtual world, e.g. color, depth...
- 2) references for judging the virtual objects' motion near this gap
- 3) visual cues that help the user to understand the virtual world on two displays as a whole

Theoretically, lack of the above information may hinder task performance in some cases. Understanding GBD may help us effectively configure displays for VE and augmented reality systems to reduce this effect. This leads to several specific research questions:

- 1) *Does the gap between displays affect task performance and usability of the system? What kinds of tasks are likely to be affected? How severe is this effect?*

The gap may affect both users' cognition and their action. For example, previous research has shown that the missing wall in the four-screen CAVE leads to breaks in presence (BIPs) [18]. In this case, users are distracted by the real-world scene in the missing wall area. But will this distraction actually affect users' performance on their central tasks? How severe is this effect? What kinds of tasks are affected? Through our experiments, we try to find empirical evidence to answer these questions.

According to previous research on the color-size illusion [24] and depth perception in VEs [9, 12], we thought GBD might have a noticeable effect on tasks involving low-level spatial perception and cognition. Hence, we decided to mainly use spatial perception and cognition tasks in our experiments.

2) *What is the best way to fill in the gap for different tasks? Should we reduce real world stimuli or not?*

If GBD really affects user performance or system usability, this second question will be worth investigating. As we know, improving the quality of the sensory stimuli displayed in the virtual display (e.g., increasing the resolution and visual fidelity of the image) could increase task performance or system usability. The hypothesis that naturally follows is that reducing stimuli from the GBD will also improve the efficiency and usability of VEs. Our rationale is that reduced real-world distraction may result in better perception of and attention to stimuli from the virtual world, and consequently a greater ability to concentrate on the task at hand.

The idea of reducing real-world distractions has already been used in some VEs. For example, the “blindness” found on many HMDs, or the use of a dark room for a CAVE™ [4] serves to reduce the visual distraction from the real environment. These designs are based on an untested hypothesis.

3) *What is the tradeoff between GBD and FOR for different tasks? Is there a threshold that indicates the minimum gap size that does not affect users' performance?*

This question seems to be task specific and depends on the answers to the previous questions. We leave it as future work.

In our work (originally described in [27]), we used a four-screen CAVE as the experimental platform and compared the effect of GBD (the missing back wall) on users' task performance in two different conditions: a low-stimulus GBD condition and a high-stimulus GBD condition. The low-stimulus condition was created by hanging a black cloth across the missing back wall of the CAVE. The high-stimulus condition was created by projected animations and real human motion outside the CAVE. We used three different tasks in the experiment: the gap estimation task, the destination prediction task and the virtual world visiting task. The three tasks were designed to cause different levels of awareness of the gap between the two CAVE side walls. This experiment partially addressed our second research question.

In this paper, we extended the above studies with a follow-up experiment that compares the low-stimulus condition with the no-GBD condition, where the virtual world is displayed to fill in the gap. The purpose of this experiment is to address the first question, i.e., to find out how severe the effect of GBD is. This experiment also helps to test the validity of the two tasks. If the task is sensitive to

different GBD conditions, there should be a significant difference in user performance between the low-stimulus and no-GBD conditions. We used the gap estimation task and the destination prediction task because there was a performance difference for these two tasks in the previous experiment.

2 RELATED WORK

We summarize related literature from two fields: virtual reality and cognitive psychology.

2.1 *Virtual Reality: Breaks-In-Presence and Hybrid Presence*

Researchers within the virtual reality field have conducted many experiments that evaluate the effects of immersion on people's sense of presence in immersive VEs [14, 15, 16, 17, 19, 21]. The well-known Break-In-Presence (BIP) theory states that in a situation where the user is exposed to stimuli from both the virtual and the real world, the user may stop responding to the virtual stream and respond instead to real sensory stream [16, 18]. Slater et al. tried to find a physiological signature for BIPs [19]. They hypothesized that the experience of a BIP might be a stress-inducing event. They measured subjects' Skin Conductance Response (SCR) and Blood Volume Pulse (BVP) when a BIP occurred. Both SCR data and BVP data showed a peak at the moment that a BIP was signaled. Since presence is a subjective factor and is hard to measure directly [20], we avoid measuring the sense of presence in our research. Instead we focus on linking the GBD component of immersion with measurable human performance and system usability.

Spagnoli and Gamberin claimed that users' response to a VE, which is inevitably a hybrid environment, is also hybrid [22]. Their hypothesis was supported by phenomenological observation. They found that users may not have a clear boundary between the real world and the virtual world in their minds. For example, when a technical problem comes up, the real medium becomes visible. Users may attempt to fix the problem in the real world while continuing their actions in the virtual world. As in other working environments, people make sense of VEs by interacting with them at different levels. In our experiments, we wish to determine whether reduced real-world distractions can help users make sense of the environment and hence achieve better performance.

Razzaque et al. [14] verified that users' sense of presence was significantly reduced when more of the (missing) back wall was seen. So they designed an auto-rotation method to reduce the user's chance of seeing the back wall. Since we are investigating whether this missing wall may affect task-specific performance and usability, we want to increase the chance that users will face the missing wall in our experiments.

2.2 *Cognitive psychology: Attention and Performance*

Many researchers have suggested a link between presence and performance, but it is not clear whether there is one. In

[15], attention is believed to be one of the three major factors that affect the user's sense of presence. We hypothesize that attention may also affect users' performance in immersive VEs.

A well-known theory in cognitive psychology research is C. Folk's thermostat theory [6, 7]. It states that a bottom-up distraction with the same properties as the objects of a person's attention can temporarily capture attention, leading to a delayed response. It was also found that humans' top-down control of selective attention is very effective. Irrelevant distraction has virtually no effect on human performance [6, 7, 11]. Cater et al. [2] showed that in some cases, human subjects failed to notice a change in the quality of an image when concentrating on their central tasks. These findings were obtained with micro-level tasks under well-controlled conditions. Do these results still hold for macro-level tasks that people perform in an immersive VE? We hypothesize that real-world distractions can occasionally capture human attention and hence decrease task performance in immersive VEs. Our experiments are designed to provide supporting evidence for this hypothesis.

2.3 Spatial Perception, Cognition and Judgment

Several experiments have shown that people's spatial perception in VE is different than that in a real environment [9, 12]. Distance to faraway objects is typically underestimated. All of this prior research assumed no GBD in the experiment settings. We think research on GBD may help answer these questions because VE systems involving GBD allow us to directly compare people's spatial judgment in the real world and in the virtual world.

3 SYSTEM IMPLEMENTATION

In this section, we describe the hardware and software used in our experiment.

3.1 Hardware

The three tasks were implemented in a four-screen CAVE™ driven by an SGI Onyx2. We used an Intersense IS-900 VET head and hand tracking system. This included a 6-DOF head tracker and a wand, and was used to input 3D position and orientation data. Stereo shutter glasses were also used.

3.2 Real-World Distraction Settings

We used only one independent variable in all the three experiments: the level of visual distraction in the open space created by the missing CAVE wall. The low stimulus area was created by occluding the real world from the user, using an 11'×13' black cotton cloth (Fig. 2).

For the high stimulus condition, we included several real-world distractions (Figs. 3, 4): people walking back and forth in the room, and two projected display distractions. We provided different levels of distraction on the two projected displays. One of them showed bright, dynamic morphing geometric shapes, which provided a strong distraction. The

other was a game demo, which provided a weaker distraction.



Fig. 2: CAVE in the low-stimulus GBD condition: a black cloth covering the missing wall.

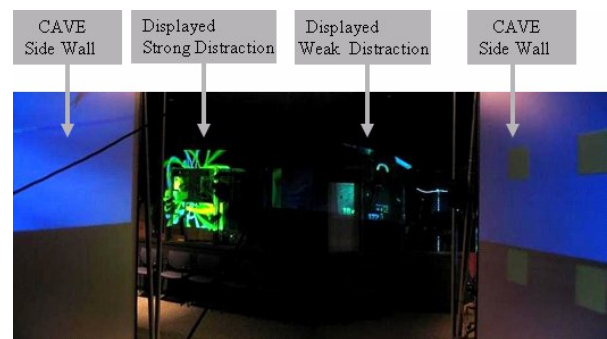


Fig. 3: CAVE in the high-stimulus GBD condition. A view of the displayed distractions from inside the CAVE.

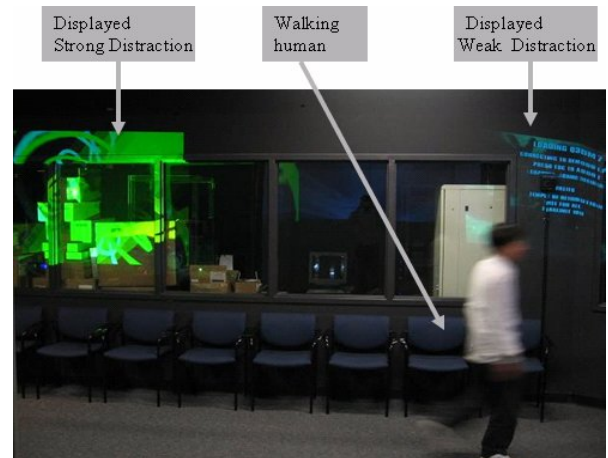


Fig. 4: CAVE in the high-stimulus GBD condition. A view of the missing wall from inside the CAVE, showing walking human and displayed distractions.

4 TASK DESIGN

From previous research and our experience, we noticed that when users perform tasks in an immersive VE, they are often too involved in their primary task to notice small distractions. Even when they do, the time of attention shift may be very short. Thus, our experiments need to be able to isolate a subtle effect. After trying some initial experimental designs, we came up with criteria for promising experimental tasks:

- 1) Look for cognition-dominated tasks with few physical actions. This guideline is based on the hypothesis that distraction has little effect on motor tasks such as travel. The more motor time is factored into our total task time, the more noise is introduced, and the less obvious the effect of distraction.
- 2) Let the tasks occur near the boundary between the VE and the real world, so as to emphasize the difference between the conditions. This is because previous research indicates that the distraction effect might be too subtle to measure.
- 3) Prevent users from concentrating on a small area, lest they fail to notice changes occurring in the real world.
- 4) Let the dominant feature of the distraction resemble the dominant feature of the central task. For example, if we want the user to search for objects of different shapes, the real-world distraction should also contain many such shapes.

Based on the above criteria, we designed a variety of tasks. Then we ran an exploratory study to filter out the unpromising experiments and fine-tune the promising ones. Finally, three tasks were selected for the formal study: Gap Estimation, Destination Prediction, and Crayoland Visit. These three tasks elicit different levels of awareness of the real-world distraction. The Gap Estimation task is cognition-dominated, and involves very little user motion. A simple selection function is added in Destination Prediction, which, like the Gap Estimation task, is cognition-based and requires the user to notice the changes occurring in the real world. In the Crayoland Visit task, the user travels through a virtual world. User recollection of the spatial arrangement of objects in the virtual world is tested after navigation.

4.1 Gap Estimation Task

In this task, the user was shown a set of balls arranged in a horizontal line that extended from the left CAVE wall, through the missing CAVE wall, and onto the right wall (Figs. 5, 6). The user was to guess the number of balls in the missing wall, given the number, spacing and size of the balls she could see to the left and right sides of the missing area. The dependent variable was the number of balls guessed. This experiment was implemented using the DIVERSE library [5].

To reduce the learning effect, the distance of the ball to the user, the distance between the balls, and the number of the balls were randomly chosen between a range.

The subject was told to stand at the position shown in Fig. 6. The subject was asked to intuitively guess the number of the missing balls based on the information provided on the two side walls. To avoid a learning effect, we did not feed back the correct answer to the subjects after their estimation. Each subject did 10 trials for each condition. The sequence of the two conditions was counterbalanced.

The estimated number of missing balls as well as the actual number was recorded by an experimenter. The time to make

each estimation was recorded by the software.



Fig. 5: User performing gap estimation task in the CAVE

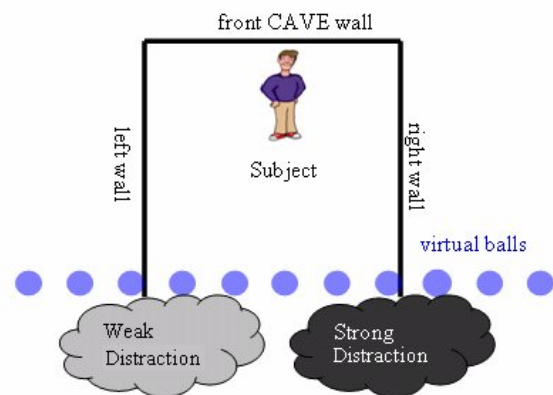


Fig. 6: Gap estimation task diagram. Users cannot see the virtual balls on the back wall. Instead they see weak and strong animation distractions displayed in the open back wall area.

4.2 Destination Prediction Task

This task involved a ball flying from one point to another, and passing through the open CAVE wall. The ball would land in any of the nine squares in a vertical, 3×3 matrix arrangement. The user task was to predict which square it would be, judging from the motion path of the ball. This was done using a ray cast from the wand to choose the most appropriate square (Figs. 7, 8). The ball's starting position was randomly selected within a square area parallel to the nine blocks. When the user hit a button on the wand, the ball started to move along a straight line with a constant speed. The ball would stop in the missing wall area and wait for the user to predict a destination. Once a destination was predicted, the ball would continue its movement. This task was implemented using the DIVERSE library [5].

The dependent variables were the user's correctness rate and the time taken to make a prediction. The subject got three points when the prediction was correct, and one point when the predicted destination was on the same row or column as the actual destination.

During the exploratory study, we did not find a large difference between the conditions for this task. Several

improvements were made based on the exploratory study.

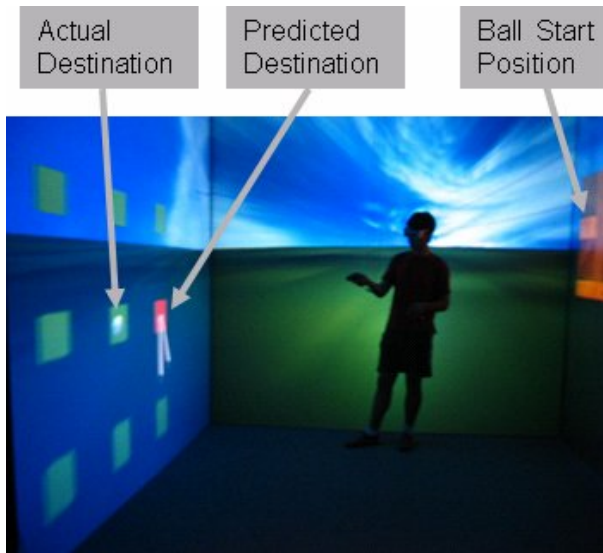


Fig. 7: User performing destination prediction task in the CAVE

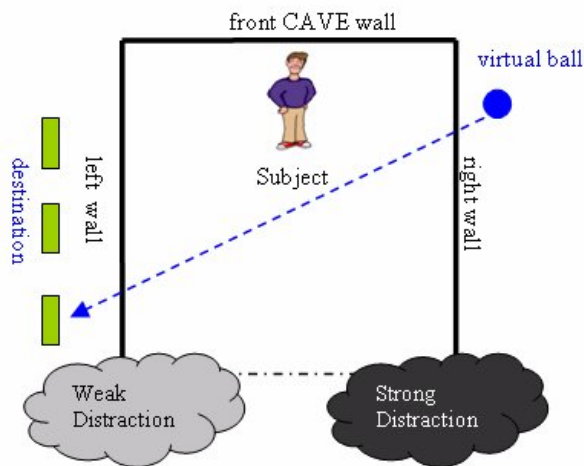


Fig. 8: Destination prediction task diagram.

The squares were contiguous before the study, thus making it difficult for the user to distinguish between the squares. The motion path of the ball was improved so that it always left the side wall's side boundary instead of the upper or lower boundary, since only balls leaving the side boundary can enter the missing back wall area. We changed the balls' starting position so that they could travel a greater distance on the side wall, giving the user more time to perceive the motion. Finally, a starting plane was added at the ball's start position in order to give the user a better depth cue about the ball's initial position.

Fig. 8 demonstrates the subject's position and orientation, and other experiment settings. Each subject did 10 trials for each condition. The sequence of the two conditions was counterbalanced.

4.3 Crayoland Visit Task

The Crayoland visit task was performed in the pre-existing Crayoland demo environment. Crayoland is a serene environment with trees, sunny skies, flowers, mountains,

butterflies, a bungalow, a duck pond, and buzzing bees [3].



Fig. 9: User performing Crayoland visit task in the CAVE

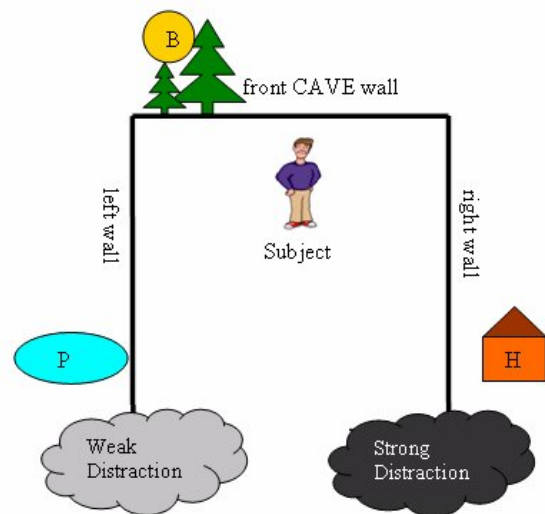


Fig. 10: Crayoland visit task diagram. Subjects walk from the Beehive (B) to the pond (P) and then to the house (H).

For our study, the user navigated through the environment, using the wand (Figs. 9, 10). The formal Crayoland task required the user to navigate Crayoland for a fixed time of two minutes. They walked along a specific path: start from the bee hive, ford the pond, enter the bungalow and come back to the bee hive.

This task was between-subjects to eliminate learning effect. During the experiment, a log of the participant's head orientation in 360-degree CAVE space was generated. After two minutes, the environment was turned off and the user was asked to answer questions that required her to recall the objects in Crayoland, as well as their spatial arrangement. The first questionnaire contained a list of twenty-seven objects, sixteen of which were actually present in Crayoland. The user had to circle the objects she could remember seeing in the environment. The second questionnaire required the user to represent four specified key objects in Crayoland, in terms of their relative size and relative location to each other.

Our dependent variables were the user's ability to recall spatial information, and the orientation of the user's head during the task process. One restriction we had for this task

was that the user was positioned about one foot from the front wall of the CAVE (see Fig. 10), and was instructed to avoid facing the front wall, but to try to perform the entire navigation task using the other CAVE walls, and facing the missing back wall.

The participant was taught wand navigation using another environment, Performer Town, so that the Crayoland environment would be new to her. When the subject had become familiar with navigation in the CAVE, we loaded Crayoland and started our monitoring software to record the subject's head orientation. The subjects were told to find the beehive, move from the beehive through the pond, and finally to the house. They were not instructed to move quickly. After two minutes, the task ended. The subject was then asked to complete the two questionnaires.

5 EXPERIMENT 1: FILL GBD WITH WHAT STIMULI ?

The first formal study was conducted with twenty-two unpaid participants, of whom there were nine females and thirteen males. The age range was between twenty-one and thirty-seven years old. Seven of the participants were familiar with the CAVE environment, and fourteen did not play video games at all. Each user took a total of about forty minutes to complete the tasks. Each subject performed the gap estimation task and the destination prediction task in both the high-stimulus and low-stimulus conditions. For the Crayoland visit task, each subject only perform once, either under the high-stimulus or low-stimulus condition.

5.1 Gap Estimation Task

Our original hypothesis was that with the black cloth draped on the missing wall, the users would perceive the gap to be smaller than they find it to be under the high-stimulus condition. In one sense, this is good, because in a world where the only two options for the missing wall are low-stimulus material or high-stimulus real world (and not a continuation of the virtual world through a CAVE back wall), it would be better for this area to be perceived to be as small as possible, so that information in the left and right walls would seem more continuous. However, if the VE requires users to have an accurate sense of scale and distance, the most important metric would be the comparison of the user's estimation of the gap to the actual size of the gap.

The main finding is that the estimated number of missing balls tends to be smaller when the black cloth is on.

Fig. 11 shows the distribution of trials at different error levels. On average, each subject underestimated the number of balls by 0.18 when the cloth was on. But when facing the distraction, each subject overestimated the number of balls by 1.45 on average.

This result is consistent with our hypothesis, but it was not significant based on a t-test analysis. This might be due to the variances of users' depth perception and the randomness of trials. We observed that some subjects had abnormal estimations for some trials. This abnormality might have

been caused by a loss of proper depth perception of the displayed balls.

On average, 11 out of 22 subjects estimated fewer balls in the black cloth condition than in the distraction condition. Six subjects made very similar estimations on average. Only five subjects estimated more balls in the black cloth condition. As for estimation accuracy, the black cloth condition was no better than the distraction condition. Nine out of 22 subjects' estimations were more precise under the distraction condition. Five subjects estimated better with the black cloth on. The other eight subjects performed about equally well in the two conditions.

We also measured the time to finish the task and found no significant difference between the two groups.

Our interpretation of the difference in the average estimation error is that with the real-world distraction, the subjects' perceived gap is larger than the actual gap. The real-world distraction is dynamic and may leave a stronger impression in the mind than the static VE scenario. When the black cloth is on, the real world stimuli are reduced, so the perceived gap is smaller than the actual value. This is consistent with some experimental results from psychology: the perceived size of a region is influenced by the color (hue), the brightness and the saturation of that region [24].

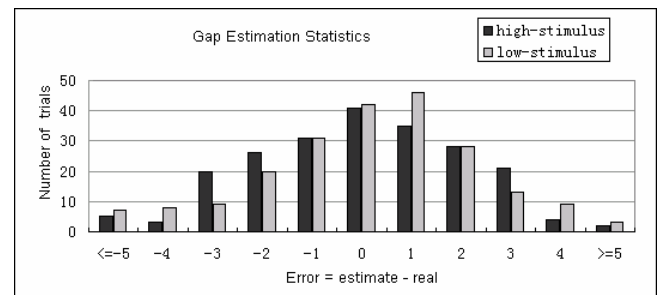


Fig. 11: Distribution of trials with different levels of errors in gap estimation Task. Error value is the estimated number of balls minus the real number of balls. Positive error means overestimate, negative error means underestimate.

5.2 Destination Prediction Task

We hypothesized that users would prefer to do the task with the black cloth on the missing wall, and that their precision of prediction would also be slightly better in the low-stimulus condition.

The main result is that subjects with real-world distraction achieved higher prediction precision.

The mean score of subjects with distractions and cloth were 22.68 and 19.32, respectively. As shown in Fig. 12, more trials under the distraction condition received a score of 3.

We did a two-tailed T-Test to analyze the difference between the mean score of the two groups. It showed a significant difference with $t = 2.59$ ($p < 0.05$).

We found that 16 out of 22 subjects predicted more precisely with real-world distraction. Three subjects performed equally well in the two conditions. Only three subjects performed better with the black cloth on.

Considering the effect of task sequence on subjects' performance, we also analyzed the scores from only the first trials of each subject. The trend was similar, but not significant.

By observing the correlation between each subject's performance on the gap estimation and destination prediction tasks, we found that accurate gap estimation often led to accurate destination prediction. But for some subjects, this was not true.

We also measured the task completion time and found that subjects' time to make prediction was often correlated to their score. In the majority of cases, destination prediction tasks performed in the distraction condition took less time. The cognitive load caused by the distraction did not play a major role in users' performance.

Our interpretation of this result is that with real-world distraction, subjects can use more real-world objects as references to judge the ball's motion. This is consistent with some subjects' comments. Some subjects felt that when the black cloth was on, the balls suddenly "disappeared into the black area", and they found it difficult to predict the balls' motion.

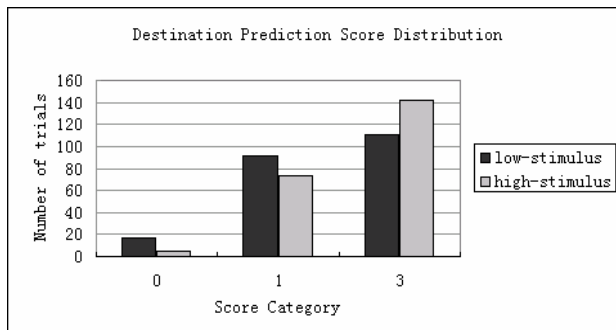


Fig. 12: Score Distribution of Destination Prediction Task.

5.3 Crayoland Visit Task

Our hypotheses for this experiment were:

- 1) User recall of Crayoland objects would be improved with low-stimulus condition.
- 2) Users would be more likely to keep the open wall in view if the real world was occluded (low-stimulus condition).
- 3) Users would prefer the low-stimulus condition.

We found no significant differences between the conditions based on object or environment recall. In the black cloth condition, the 10 subjects recalled 11.0 out of 16 objects with 0.8 false positives on average. The recall average was 10.7 with 0.7 false positives in the distraction condition. The environment recall was measured by scoring the map drawn by the subjects with two criteria: relative orientation of objects and relative distance of objects. The best possible score for each criterion was 4. Subjects in the black cloth condition received average scores of 3.2 and 2.9 for the orientation and distance criteria respectively. Subjects in the distraction condition received average scores of 3.0 and 3.2. The performance similarity between the two groups indicates

that the effect of different levels of peripheral distraction for this task might be too subtle to measure using our method.

The head orientation data showed some difference between the two conditions. When the cloth was on, the subjects spent more time facing the direction of the missing wall (shown in Fig. 13). We suppose that the users tended to look straight forward to keep their head in a comfortable position. But with the distractions in the high-stimulus condition, they subconsciously turned their head to face interior of the side walls in order to avoid distractions.

The Crayoland visit task did not result in a significant performance difference between the two conditions. We think this may be due to several factors. First, the effect of real world distraction on users' performance is very subtle when the user concentrates on one task. Second, the shutter glasses used in the CAVE narrow the subjects' field of view. This lowers the effect of peripheral real-world distraction.

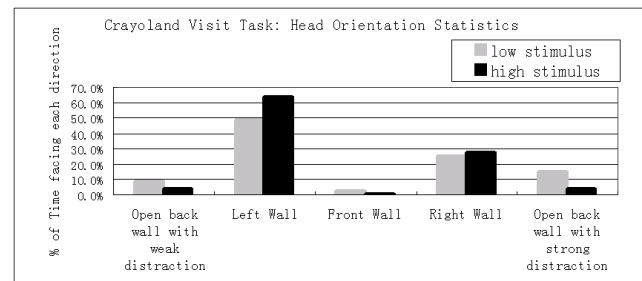


Fig. 13: The percentage of time that subjects facing different CAVE walls in Crayoland visit task.

5.4 General Findings

In the post-experiment questionnaire, we asked the subjects which condition they felt more comfortable working in. Seven out of 22 subjects preferred the condition in which the black cloth occluded the real world. Two preferred the condition without the cloth. The others felt that there was no difference.

We also asked the subjects in which condition they performed better. Five subjects answered that the black cloth condition seemed to produce better performance, three answered the distraction condition, and the others could not tell.

Once the experiment was completed, one experimenter had a short interview with each subject. We found that before starting the experiment with the distraction condition, all users were aware of the displayed distractions when they stood in the CAVE. However, they normally did not notice these distractions when performing the tasks.

6 EXPERIMENT 2: HOW SEVERE IS GBD?

After the first experiment, we formalized the "real world distraction" problem into the GBD problem. We noticed that one essential question remained unclear: *how severe is the GBD effect?* To answer this question we need to compare the GBD condition with a baseline condition, where no GBD

exists between the two side walls. We can create this condition by letting the user face the front wall, where the virtual world will be displayed; we call this the no-gap condition. This experiment also helps to test the validity of the two tasks. If the task is sensitive to different GBD conditions, there should be a significant difference in user performance between the black cloth and no-gap conditions. We used the gap estimation task and the destination prediction task because we saw performance differences in the previous experiment for these two tasks.

This experiment was conducted with fourteen unpaid participants, of whom there were six females and eight males. The age range was between twenty-two and fifty years old. Four of the participants were familiar with the CAVE environment, and six of them had participated in the first experiment or exploratory study.

The black cloth condition in the experiment was equivalent to that used in experiment 1. In the no-gap condition, we displayed the “background” of the virtual world; that is, everything except the balls.

6.1 Gap Estimation Task

Estimation Accuracy: On average, each subject made 1.1 fewer errors under the no-gap condition than the black cloth condition. The difference was not significant but exhibited a strong trend ($p=0.08$).

Estimation Tendency: The estimated number of balls was very similar in the two conditions (Fig. 14).

The results indicated that this task was not quite suited for comparing controlled GBD conditions in such a small user group. Because we did not tell users the real number of missing balls after their guesses, users showed a tendency throughout the trials to overestimate or underestimate the number of balls. This caused a large between-subject variance.

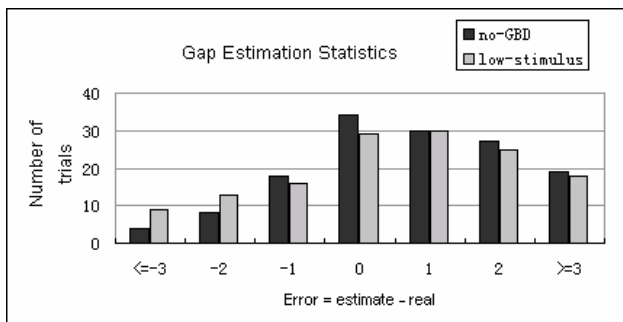


Fig. 14. Distribution of trials with different levels of errors. Error value is the estimated number of balls minus the real number of balls. Positive error means over-estimate, negative error means under-estimate.

6.2 Destination Prediction Task

The major conclusion from the destination prediction task was that users' prediction accuracy under the no-gap condition was better than the black cloth condition (Fig. 15).

We performed a two-tailed T-Test to analyze the difference between the mean score of the two conditions. The difference was significant, with $t=2.58$ ($p<0.05$).

We were not able to draw any conclusion when comparing the prediction accuracy under the no-gap condition in this experiment and the distraction condition from the previous experiment. A large variance in scores between the users in these two experiments kept us from drawing any reliable conclusion.

We also compared the prediction precision for only the first trials under the three conditions, in order to avoid a learning effect. The no-gap condition had the highest score, followed by the distraction condition. The black wall condition had the lowest score for the initial trials.

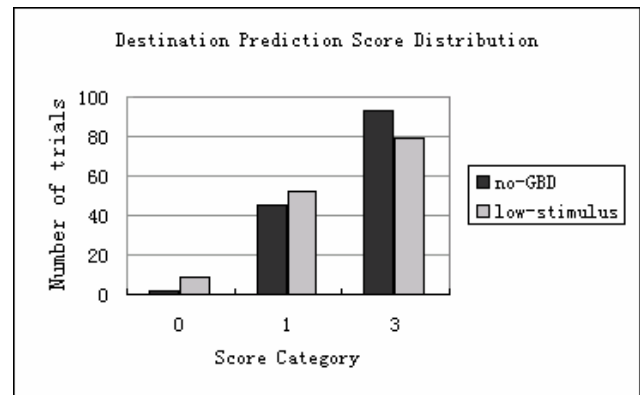


Fig. 15. Score Distribution of Destination Prediction Tasks

7 CONCLUSIONS AND FUTURE WORK

Through two experiments, we partially addressed the first two research questions proposed in the introduction of this paper:

1) *Does the gap between displays affect user's spatial perception and cognition? How severe is this effect? What kinds of tasks are likely to be affected?*

Our experiment showed that the level of distraction has a measurable effect on users' performance for at least some tasks. The relationship between the level of distraction and users' performance is more subtle than our initial hypothesis, however.

2) *What is the best way to fill in the gap for different tasks? Should we reduce real world stimuli or not?*

We did not find that reducing the level of distraction with a low-stimulus area consistently increases or decreases user performance. Rather, the effect depends on the specific task and the specific VE scenario. For better spatial perception, it may be better to fill in the gap with an appropriate amount of stimuli than to remove all stimuli.

These experiments are our first step to understand the relationship between the real-world setting and the virtual world content in immersive VEs. In the future, we can vary the background of the VE and investigate how the difference between the virtual scene and the real-world setting affects user performance. Another important extension would be to design some tasks that will allow the user to use the CAVE in a normal way (facing the front wall instead of the back wall), but that will also subtly guide the user to encounter the missing back wall at some point in the VE experience. In all

three tasks we artificially asked people to face the missing wall, which is the exact opposite of the real usage case. In realistic use, the missing wall might be even more distracting, because the users are fully immersed in the virtual world and find themselves facing the missing wall abruptly, when they are not prepared for it. The last but not least idea for significant future work is to find the tradeoff between GBD and FOR for different tasks.

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REFERENCES

- [1] Bowman, D., Kruijff, E., LaViola, J., and Poupyrev, I. 3D User Interfaces: Theory and Practice, Addison-Wesley, 2004
- [2] Cater, K., Chalmers, A., and Ward, G. Detail to attention: Exploiting visual tasks for selective rendering. In Proceedings of the 2003 EUROGRAPHICS Symposium on Rendering, EUROGRAPHICS, 2003, 270-280.
- [3] Crayoland, <http://www.evl.uic.edu/pape/projects/crayoland/>
- [4] Cruz-Neira, C., Sandin, D.J., DeFanti, T.A., Kenyon, R.V., and Hart, J.C. "The CAVE: Audio Visual Experience Automatic Virtual Environment," Communications of the ACM, Vol. 35, No. 6, June 1992, 65-72
- [5] DIVERSE, <http://diverse-vr.org/>
- [6] Folk, C. L., Remington, R. W., and Johnston, J. C. Involuntary Covert Orientating is contingent on attentional control settings. Journal of Experimental Psychology: Human Perception and Performance, 1992, 1030-1044.
- [7] Folk, C.L., Remington R.W. Selectivity in distraction by irrelevant featural singletons: evidence for two forms of attentional capture. Journal of Experimental Psychology: Human Perception and Performance, 1998, 24(8):47-58.
- [8] Kjeldskov, J. Interaction: Full and Partial Immersive Virtual Reality Displays. In Proceedings of OzCHI 2001, 77-83.
- [9] Messing, R. and Durgin, F. Distance Perception and the Visual Horizon in Head-Mounted Displays. ACM Trans. Appl. Percept. 2, 3 (Jul. 2005), 234-250.
- [10] Ni, T., Bowman, D. A., and Chen, J. 2006. Increased display size and resolution improve task performance in Information-Rich Virtual Environments. In Proceedings of the 2006 Conference on Graphics interface. ACM International Conference Proceeding Series, vol. 137., pp. 139-146.
- [11] Pashler, H., Johnston, J.C. and Ruthruff, E. ATTENTION AND PERFORMANCE. Annual Review of Psychology, Feb. 2001, 52: 629-651.
- [12] Plumert, J. M., Kearney, J. K., Cremer, J. F., and Recker, K. Distance perception in real and virtual environments. ACM Trans. Appl. Percept. 2, 3 (Jul. 2005), 216-233.
- [13] Polys, N., Kim, S., and Bowman, D. Effects of Information Layout, Screen Size, and Field of View on User Performance in Information-Rich Virtual Environments. Proceedings of the ACM Symposium on Virtual Reality Software and Technology, 2005, pp. 46-55.
- [14] Razaque, S., Swapp, D., Slater, M., Whitton, M., and Steed, A. Redirected Walking in Place. Eighth EUROGRAPHICS Workshop on Virtual Environments, May 2002, 123-130.
- [15] Schubert T., Friedmann, F., and Regenbrecht, H. Decomposing the sense of presence; factor analytic insights. In 2nd International Workshop on Presence, 1999, 3-23.
- [16] Slater, M. and Steed, A.J. A virtual presence counter, Presence: Teleoperators and Virtual Environments, 2000, 9(5):413-434.
- [17] Slater, M., and Wilbur, S. "A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments", Presence: Teleoperators and Virtual Environments, 1997, 603-616
- [18] Slater, M. A Note on Presence Terminology. Presence-Connect, vol. 3, 2003.
- [19] Slater, M., A. Brogni, and A. Steed, Physiological responses to breaks in presence: a pilot study. In The 6th Annual International Workshop on Presence, 2003, 3-23.
- [20] Slater, M. How Colorful was Your Day? Why Questionnaires Cannot Assess Presence in Virtual Environments. Presence, 2004, 13(4): 484-493.
- [21] Slater, M. Linakis, V., Usoh, M., and Kooper, R. Immersion, Presence, and Performance in Virtual Environments: An Experiment using Tri-Dimensional Chess. ACM Virtual Reality Software and Technology, 1996, 163-172
- [22] Spagnoli, A. and L. Gamberini, Immersion/emersion: Presence in hybrid environments. In The 5th Annual International Workshop on Presence, Oct. 2002, 9-11.
- [23] Tan, D. S., Gergle, D., Scupelli, P., and Pausch, R. Physically large displays improve performance on spatial tasks. ACM Trans. Computer-Human Interaction 13, 1 (Mar. 2006), 71-99.
- [24] Tedford, W. H. Jr, S. L. Berquist, and W. E. Flynn, The Size-Color Illusion, The Journal of General Psychology, 1977, 145-149.
- [25] Tyndiuk, F., Lespinet-Najib, V., Thomas, G., and Schlick, C. Impact of large displays on virtual reality task performance. In ACM SIGGRAPH 3D, 2003, 55-58.
- [26] Usoh, M., Catena, E., Arman, S., and Slater, M. Using Presence Questionnaires in Reality. Presence: Teleoperators & Virtual Environments, 2000, 497-503
- [27] Wang, Y., Otitoju, K., Liu, T., and Kim, S. Evaluating the effect of real world distractions on user performance in immersive virtual environments. In Proceedings of the ACM Symposium on Virtual Reality Software and Technology, 2006

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