# Supporting Cognitive Processing with Spatial Information Presentations in Virtual Environments

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# Abstract

While it has been suggested that immersive virtual environments could provide benefits for educational applications, few studies have formally evaluated how the enhanced perceptual displays of such systems might improve learning. Using simplified memorization and problem-solving tasks as representative approximations of more advanced types of learning, we are investigating the effects of providing supplemental spatial information on the performance of learning-based activities within virtual environments. We performed two experiments to investigate whether users can take advantage of a spatial information presentation to improve performance on cognitive processing activities. In both experiments, information was presented either directly in front of the participant, at a single location, or wrapped around the participant along the walls of a surround display. In our first experiment, we measured memory scores and analyzed participant strategies for a memorization and recall task. In addition to comparing spatial and non-spatial presentations, we also varied field of view and background imagery. The results showed that the spatial presentation caused significantly better memory scores. Additionally, a significant interaction between background landmarks and presentation style showed that participants used more visualization strategies during the memorization task when background landmarks were shown with spatial presentations. To investigate whether the advantages of spatial information presentation extend beyond memorization to higher level cognitive activities, our second experiment employed a puzzle-like task that required critical thinking using the presented information. Focusing only on the effects of spatial presentations, this experiment measured task performance and mental workload. The results indicate that no performance improvements or mental workload reductions were gained from the spatial presentation method compared to a non-spatial layout for our problem-solving task. The results of these two experiments suggest that supplemental spatial information can affect mental strategies and support performance improvements for cognitive processing and learning-based activities. However, the effectiveness of spatial presentations is dependent on the nature of the task and a meaningful use of space, and may require practice with spatial strategies.



*Keywords: virtual environments, memory, cognition, learning, space*


**Abbreviations**

FOV: field of view; VR: virtual reality; VE: virtual environment

# Introduction

Training and educational applications are often used to help their operators learn new skills or concepts. For many types of training applications, immersive virtual reality (VR) systems are used to present virtual practice scenarios that appear to visually surround the users in 3D space. VR systems generally provide users with interactive control of a 3D world through a first-person perspective, often taking advantage of features such as head-based image rendering, stereoscopic displays, and the ability to interact though physical movements within the virtual environment (VE). Such systems have been successfully used for vehicular operation (e.g., Brooks 1999) and medical training (e.g., Quarles et al. 2008; Seymour et al. 2002). Because VR training scenarios are often designed to simulate real situations, the design of the VE is generally fairly straightforward for such applications.

On the other hand, for educational applications meant to help teach general concepts and abstract principles, the design must be carefully and creatively constructed in order to support (and not detract from) the learning objectives (Wickens 1992; Winn and Jackson 1999). Although VR technologies have been used for a variety of applications to facilitate such learning (e.g., Dede et al. 1999; Johnson et al. 1998; Roussou et al. 2006), the design features needed for successful educational applications are not well understood. Greater knowledge of what features of 3D systems support different levels of cognitive processing is needed to understand how to effectively design VR applications that are conducive to learning activities.

While researchers have suggested a variety of ways that VEs could be beneficial for learning (e.g., high levels of interactivity, support for active learning, social learning environments), all educational VEs share the challenge of how to best present learners with new information within 3D space. Many VEs have faced this challenge directly, implementing applications in which information—in the form of text, audio, or graphics—is situated at specific locations in the environment. Such spatial mappings are common in information-rich virtual environments, in which additional information is mapped to particular objects or locations (Bowman et al. 2003). For instance, Bowman et al. (1999b) presented an immersive virtual zoo application for habitat design education that allowed users to view textual information coupled with various habitat components spread throughout the environment. Current, commonly-used VEs also employ the same approach. Consider Second Life (Rymaszewski et al. 2007), a web-based, multi-user, desktop VE that allows users to explore and interact through graphical representations of themselves (known as avatars). Boulos, Hetherington, and Wheeler (2007) describe two Second Life environments, HealthInfo Island and the Virtual Neurological Education Center, that allow users to learn about health and medical information by visiting virtual information displays at various locations within the environment. The information locations are organized with the help of virtual buildings, rooms, and landmarks in the VE. Such spatial organizations could potentially aid learning by supporting spatial indexing—allowing locations to be used as references to information (Pylyshyn 1989). These spatial mappings provide learners with opportunities to use a variety of spatial strategies to remember or relate various pieces of information.

Given that VEs provide large amounts of virtual space and allow users to view information relative to their own bodies within that space, we investigate how users can take advantage of this spatial organization to support learning and information processing within 3D environments. As immersive VEs often provide enhanced cues that support spatial understanding of 3D space (e.g., Ware and Mitchell 2005; Schuchardt and Bowman 2007), we are interested in studying ways that such additional spatial cues could affect information processing.

The use of 3D space is what makes VEs different from other forms of media. Thus, in this work, we focus on studying how the use of space affects cognitive processing. In the presented studies, we explore whether users can take advantage of a spatially-organized information display to better learn information presented through a VE. Our work investigates if and how users take advantage of spatial mappings in learning tasks. By simplifying the presentation method, we focus on comparing spatial and non-spatial information presentations for a controlled investigation of the theorized benefits of the use of space. We conducted two experiments involving basic learning exercises to investigate the effects of presentation differences on effective assimilation, understanding, and application of information. The first experimental task required the memorization of a sequence of items as a simple learning activity. The second experiment involved a critical-thinking and problem-solving task requiring higher levels of cognitive processing.

## Related Work

Learning is a complex mental activity involving perceiving new information from external stimuli, relating the new information with previously learned information, and storing the new information in memory. Information presentation should be designed to ease the strain on working memory, which can affect the ability to process information (Sweller et al. 1998).

Though researchers have suggested that VR can provide additional educational benefits over more traditional methods (e.g., Dalgarno 2002; Wickens 1992), few educational VR studies have successfully collected empirical data for evaluating learning effectiveness or level of understanding. Bowman, Hodges, Allison, and Wineman (Bowman et al. 1999a) found evidence of advantages for students who used a VR application to aid their learning of zoo habitat design, but were limited by a small sample size and no statistical significance. Dede, Salzman, Loftin, and Sprague (Dede et al. 1999) found significant advantages over more traditional methods for a VR application used to learn about electric fields, but further research is needed in order to understand what design features most contribute to learning.

In any educational study, evaluation of learning is a challenging problem and the ideal methods for the measurement of conceptual comprehension are not agreed upon (Kennedy 1999; Stasz 2001). Furthermore, depending on the target level of comprehension or skill transfer, different instructional approaches can be used (Krathwohl 2002). Rather than directly attempt a complex evaluation of conceptual learning, we simplify the process by using a memorization task and a problem solving activity for our studies.

With this approach, we extend past studies that looked to memorization as a simple learning activity. While being more manageable than complex training or learning tasks, memorization activities still require the transfer of information from a VE to an operator. Sowndararajan, Wang, and Bowman (Sowndararajan et al. 2008) performed a study comparing performance on a task involving the memorization of steps of a medical procedure. This study compared participant performance on a laptop display with performance using a more immersive system with two large-display walls. The results indicated significantly better performance with the large-display version of the VE.

In a follow up study (Bowman et al. 2009), we evaluated recall time and accuracy on a procedure memorization task involving the sequential placement of colored, geometric solids in specific locations. In this study, we compared performance differences between conditions with varying levels of visual fidelity, as compared to the visual stimuli of the real world as the highest possible level (the level of visual fidelity in VEs is sometimes referred to as ``immersion'' (Slater 2003)). That is, conditions with greater visual fidelity produced experiences that more closely resembled real-world visual experiences. The overall results indicated that higher levels of sensory fidelity improved memorization performance.

VEs with increased levels of visual fidelity provide enhanced spatial cues by leveraging common perceptual abilities (e.g., binocular disparity and motion parallax) used in day-to-day life; numerous studies have shown advantages to such immersive features for spatial tasks (e.g., Ware and Mitchell 2005; Schuchardt and Bowman 2007). Based on this idea, we concluded that the performance improvements observed in our previous study (Bowman et al. 2009) could be attributed to the superior spatial perception afforded by the higher fidelity features. We hypothesized that participants were able to take advantage of these spatial cues to utilize spatial organization and memorization strategies.

This idea is supported by a number and previous experiments and theories. Past researchers have hypothesized that different types of information may be handled by different stores in working memory (Baddeley 1998) and that it may be possible to take advantage of the multiple stores to improve task efficiency by relying on multiple types of information (e.g., Duff and Logie 2001; Wickens and Liu 1988). In a similar sense, users of spatial information presentations may be able to take advantage of spatial offloading or spatial positions as redundant cues in order to improve learning efficiency. Mandler, Seegmiller, and Day (Mandler et al. 1977) provided strong evidence that spatial information can be learned automatically, without intentional effort. In their experiment, they asked participants to study a collection of items and estimate the cost of the collection. Afterwards, the researchers tested participants' abilities to recall both the names and locations of objects. Even though the instructed task did not involve memory of locations, the accuracy of location memory was well above chance.

Being learned automatically, spatial information could be an ideal candidate as a form of redundant coding to reinforce learning and to aid the recall of other associated information features. By Pylyshyn's model of spatial indexing, locations can be used as references to other information that is not visible (Pylyshyn 1989). By this model, a location can be referenced as an index, helping recall of other information that was associated with that index. Numerous studies have provided evidence that people do refer to spatial information when recalling other information. In one such study, Richardson and Spivey (2000) asked participants to recall details about objects that were no longer visible. The study found that participants often looked to the locations where the objects were when answering the questions—even though the relevant information was no longer there.

If mapping information to locations can help learners recall information, then the virtual locations of VEs could certainly be of help for learning activities. Previous research has also shown that redundantly coding information with spatial location can support better memorization. Hess, Detweiler, and Ellis (Hess et al. 1999) demonstrated that correlating object information with locations within a grid layout improved the ability to keep track of recent object changes. While this study showed that spatially organized visual displays can improve the ability to remember information, the change-tracking task used in the experiment asked that participants remember the most recent changes of a much longer list of items. In contrast, we are more interested in learning a complete information set and the ability to use the learned information.

Thus, we build upon the previous work of the use of space to support memorization and processing with two experiments. Since previous research has shown that immersive VR improves spatial understanding and that spatial mappings have the potential to improve cognitive processing, then it follows that immersive systems could improve cognitive processing activities with spatially-presented information. Because this potential benefit depends on whether learners will, in fact, take advantage of spatial mappings during cognitive processing activities, our experiments investigate the use of space for two different learning tasks. In the first experiment, we employed a sequence memorization task to study whether participants can take advantage of spatial memorization strategies. In the second experiment, we used a problem solving task to investigate whether similar strategies could be used to aid more complex types of cognitive activities.

## Experiment I: Sequence Memorization

In our previous work (Bowman et al. 2009), we found that conditions offering higher levels of visual fidelity supported better performance on a procedure memorization task. We hypothesized that participants were able to more effectively take advantage of spatial organization strategies to improve the effectiveness of their memorization strategies, but were unable to test this claim. A greater understanding of these results is important for applying the lessons learned to designing effective educational VEs.

In the first presented experiment, we follow up on this earlier work by investigating whether or not the performance improvements for a sequence memorization task could be attributed to spatial cues and memorization strategies. The experiment was designed to investigate whether spatial information layouts could be used to support more efficient memorization of information. Closely related to the idea of using spatial locations to aid learning is the issue of how environmental details influence perception of space and the ability to use spatial mapping strategies. To address this issue, we also tested how the presence of landmarks affected performance with spatial and non-spatial presentation styles. Lastly, because spatial perception is influenced by display factors contributing to visual fidelity, we also varied field of view (FOV).

## Hypotheses

We hypothesized that providing greater support for spatial memorization strategies would result in better performance for sequence memorization. We expected that information presented in a spatial layout, with different information shown at different locations on a display, would allow better performance than a non-spatial presentation, where information is shown at the same location.

Further, based on the results of past studies (Bowman et al. 2009; Sowndararajan et al. 2008), we hypothesized that a display that offers a greater FOV would better support spatial memorization strategies. Prior studies have shown that higher FOVs can positively affect both memorization (Lin et al. 2002) and spatial learning (McCreary and Williges 1998). We hypothesized that users would achieve greater performance when provided a higher FOV with a spatial presentation and that FOV would not make a difference with the non-spatial presentation.

Additionally, we hypothesized that spatial information presentation would more strongly support participants' memorization strategies if the environment afforded clear landmarks that could be associated with the steps of the sequence. Similar to the method of loci, in which memorization is aided by associating information with locations (Yates 1974), we expected that performance would improve for the spatial presentation if landmarks and perspective cues were provided. Thus, we hypothesized that memorization scores would be greater with items displayed over background imagery for the spatial presentation, as compared to displaying items against an empty, solid background.

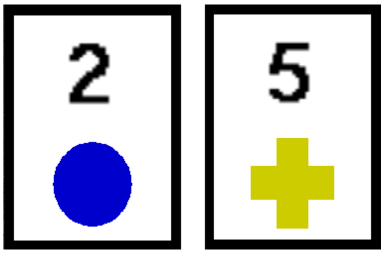


Figure 1. Examples of two cards used in Experiment I.

### Task

In this study, participants memorized a sequence of colored objects and an associated number. The objects were common 2D shapes (square, circle, triangle, cross, and star) and the numbers were whole numbers ranging from zero through nine. The shapes were colored red, blue, yellow, green, or black. For each step of the sequence, the participant was shown both the object and the associated number together on a card image (Figure 1). A sequence contained seven cards. Each card was displayed for six seconds before it was removed and the card image for the next step was displayed. Only one card was shown at a time. Participants were asked to memorize the sequence of colors, shapes, and numbers in order. Thus, the two steps for the corresponding sample cards shown in Figure 1 would be:

Step 1: blue, circle, 2

Step 2: yellow, cross, 5

The cards were presented inside a four-screen CAVE™ projection display using 1280x1024 Electrohome CRT projectors with each rear-projected wall measuring 10' wide and 9' high and a front-projected floor measuring 10' by 10'. The images were rendered with 3D perspective cues, but no stereoscopy or head tracking was enabled.  After viewing the sequence twice, participants were asked to step out of the CAVE environment and were seated in a chair facing away from the display system. The participant was then asked to verbally state the color, shape, and number for each step of the sequence.

Performance was evaluated based on accuracy and time taken to report the sequence. Accuracy was scored by counting the number of correct components (color, shape, or number) for each step of the sequence. One point was awarded for each correct component given for a step in the sequence. Because each step had three possible components and the sequence had seven steps, the highest possible score was 21. Zero was the lowest possible accuracy score. For simplicity and fairness across conditions, this scoring scheme did not adjust for special circumstances, such as when a missed step in the sequence might shift the subsequent card components.

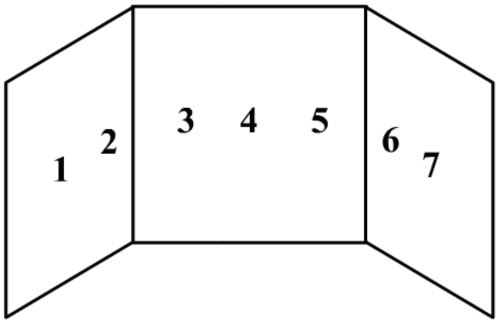


Figure 2. For the spatial presentation condition, each card of the sequence was displayed in a different location across three projection walls, one card at a time. For the non-spatial presentations, every card was displayed at position four.

## Experimental Design

To test our hypotheses, we controlled three independent variables: presentation layout, presence of landmarks, and FOV. Since it was unknown whether spatial presentations would cause differences, we chose a CAVE display in order to increase the spatial variance of locations in a spatial presentation layout and to support greater physical viewing with real-world head and body rotations. Similarly, the choice of a surround-screen display made it possible to test a large FOV, which would not have been possible with a physically small display.

Presentation layout was controlled as a between-subjects variable; each participant memorized an information sequence displayed in either a spatial or a non-spatial presentation layout on the screens of the CAVE. In the non-spatial presentation condition, each card was displayed in the same location on the front wall, directly in front of participants (this corresponds to the number four position in Figure 2). The spatial presentation condition showed the cards across the left, front, and right walls surrounding the participants. For this condition, the first card started on the left projection wall, with subsequent cards wrapping around to the front and right walls (see Figure 2). Recall that only one card was visible at a time in both conditions.

We tested the effects of landmarks by varying the background on which the cards were projected. The landmark environment condition contained a semicircle of pillars on a checkered ground plane (Figure 3). This environment was displayed over the three walls and the floor of the CAVE so that the participant was surrounded by the pillars. The complementary condition displayed an empty environment, in which the pillars and ground plane were not shown. Environment background was a between-subjects condition, so that each participant viewed all trials with either the landmark background or the empty background. Thus, the experiment had a 2x2 between-subjects design for presentation style and background landmarks.

We controlled FOV using a within subjects design so that each participant completed two trials with low FOV and two with high FOV (in randomly determined combinations). We considered performance differences when participants had a full, uninhibited FOV compared to trials which limited FOV to 60 degrees of horizontal viewing range. For the low FOV conditions, participants wore goggles that served as physical blinders to limit FOV. For the high FOV conditions, participants wore clear lab goggles having no or negligible effect on FOV. Figure 4 shows the glasses used for the experiment.

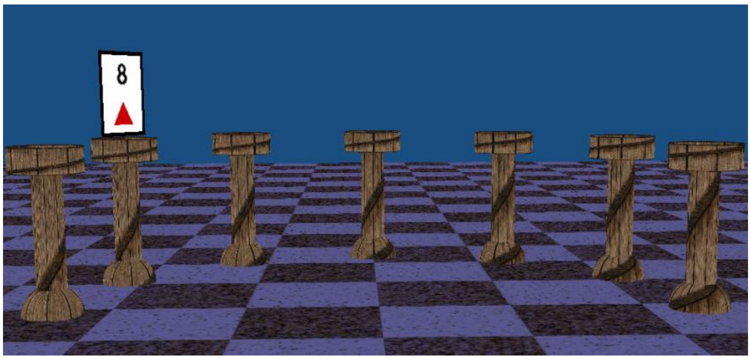


Figure 3. In the landmark environment, the cards appeared on top of pillars in a checkered environment.

Figure 4. The glasses on the left limited FOV to 60 degrees, while the control glasses on the right did not reduce FOV.

## Participants

Thirty-two university students and staff members participated in the study. An equal number of male and female participants volunteered and gender was balanced across conditions. Participant ages ranged from 18 to 57 with a median age of 20. We distributed participants across conditions by age as well as possible to limit potential confounding effects of age. The 32 participants were spread equally across the four conditions of the 2x2 between-subjects design for presentation style and landmarks. With this design, 16 participants completed the experiment with the spatial presentation and 16 with the non-spatial presentation. Similarly, 16 had background landmarks present, while 16 had blank backgrounds without landmarks.

## Procedure

Before completing any trials, participants were introduced to the CAVE system. Participants then completed a cube comparison test of spatial ability from Kit of Factor-Referenced Cognitive Tests (1976 Edition) so that we could later test for any correlations of performance to spatial aptitude.

Each trial consisted of viewing the entire card sequence twice and then verbally reporting the remembered sequence outside the CAVE. Each participant first completed a practice trial with five cards. In order to account for issues with color blindness, participants were then tested on the ability to distinguish between the colors used in the cards. Participants then completed four trials (two trials with each FOV) with sequences of seven cards. Because presentation layout was varied between subjects, each participant viewed all sequences (including the practice trial) either with the spatial wrap presentation or with the non-spatial, straightahead presentation. Participants were encouraged to rest and relax between trials and were required to take a break for at least three minutes after the first two trials in an effort to reduce any effects of mental fatigue or interference among the different sequences.

After completing the trials, we interviewed participants about the strategies used in performing the experimental task.

## Results and Discussion

To analyze the effects of our independent variables on scores and times, we performed a mixed-design ANOVA with FOV as the within-subject factor and considered presentation layout and presence of background landmarks as between-subjects variables. There was a significant main effect of presentation layout on scores with $F(1, 28) = 4.43$, $p < 0.05$. As hypothesized, scores with the spatial presentation ($M = 14.50$, $SD = 2.18$) were significantly better than scores with the non-spatial presentation ($M = 12.21$, $SD = 4.16$). Figure 5 shows means and standard errors of the means for conditions. Estimates for effect sizes and test power are presented in Table 1. No significant effect of presentation was found for time, $F(1, 28) = 0.30$, with $M = 57.45$ and $SD = 22.86$ for spatial and $M = 54.13$ and $SD = 18.65$ for non-spatial presentations.

These results do support the hypothesis that a spatial information presentation improves memorization performance for accuracy (but not recall time). This supports the explanation for the results of our previous study (Bowman et al. 2009), in which we suspected that increased visual fidelity of a VE caused significant performance improvements for a memorization activity due to the enhanced spatial cues.

While we expected that participants would be able to use a background environment and its landmarks to aid memory, the presence of such a background had no significant effect on performance, with $F(1, 28) = 1.69$ for score and $F(1, 28) = 0.20$ for time. Several participants even commented that they found the background environment to be distracting and made it difficult to record mental visualizations of the cards themselves. A similar effect was observed in a memory-of-location experiment by Jones and Dumais (1986), in which it was noted that landmarks may have only cluttered the reference space.

Because there were no significant interactions between the presence of landmarks and presentation style, with F(1, 28) = 2.22 for scores and F(1, 28) = 0.07 for time, we reject our hypothesis that presence of landmarks improves performance for spatial presentations.

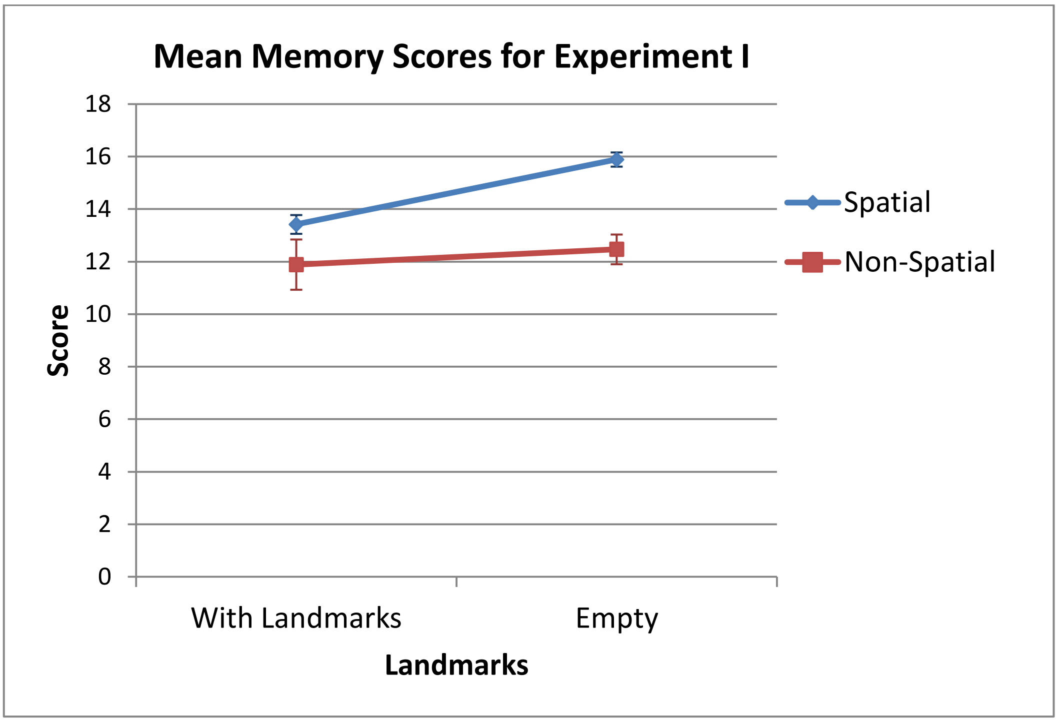


Figure 5. Means for memory scores from Experiment I with error bars for standard error of the mean. Scores were significantly higher with the spatial presentation style.

| Variable | F | p | Cohen's d | $\eta_p^2$ | Power |
|---|---|---|---|---|---|
| **Presentation** | 4.426 | 0.045 | 0.659 | 0.136 | 0.528 |
| **Landmarks** | 1.690 | 0.204 | 0.353 | 0.057 | 0.241 |
| **FOV** | 2.122 | 0.156 | 0.237 | 0.070 | 0.291 |

Table 1. Additional test details for variable effects on memory scores for Experiment I. Effect sizes and power were calculated using alpha = 0.05.

No significant differences in times or scores were found for FOV, with F(1, 28) = 2.12 for score and F(1, 28) = 0.48 for time. There were also no significant interactions between FOV and presentation layout, with F(1, 28) = 0.28 for score and F(1, 28) = 2.67 for time. We reject our hypothesis that an increased FOV improves performance for a spatial presentation.

Based on the combined results of Experiment I and (Bowman et al. 2009), we hypothesized that increasing spatial cues with spatial organization or enhanced visual stimuli could improve the effectiveness of at least some learning-based applications. The impact of such enhancements, however, depends on the task and learning environment. For example, FOV had no effect on performance in Experiment I, while an increased FOV improved performance on the procedure memorization task of our earlier study (Bowman et al. 2009).

We also conducted a two-tailed Spearman correlation test of the recall accuracy scores with the scores from the cube comparison test of spatial ability for both the spatial and non-spatial presentation methods. For participants with the non-spatial presentation, we found a significant correlation between spatial ability scores and recall scores, with $\rho = 0.54$ and $p < 0.0001$. No significant correlation was found between recall scores and spatial ability scores for the spatial presentation conditions ($\rho = 0.14$ and $p = 0.26$). These correlations suggest that individuals with higher spatial aptitudes had some advantage in the memorization task with the non-spatial display; however, this advantage was eliminated with the spatial presentation. Additional spatial cues enabled participants to compensate for lower spatial cognitive abilities (similar results have also been observed in previous studies, (e.g., Quarles et al. 2008). Combining this analysis with the significant score improvements gained with the spatial presentation, it suggests that the spatial presentation supported performance improvements regardless of individual spatial aptitude.

We also calculated point-biserial correlations of scores and times with gender for both spatial and non-spatial conditions, finding no significant correlations.

Based on the post-test interview responses, we conclude that the additional spatial cues provided in the spatial presentation did not cause participants to completely change their memorization strategies; rather, it seems that participants used the additional spatial information to supplement other strategies. Participants used whatever strategies were most natural to them (e.g., mental visualization snapshots, repetition, or the creation of patterns) with the mapping of pieces of information to locations in space helping to reinforce these strategies. We analyzed the responses from our interviews in order to categorize the general types of strategies used for the memorization task.

Participants reported using multiple types of strategies or relying on different types of memory cues simultaneously to aid memorization and recall. The most commonly reported strategies included visualizing the cards and/or their locations on the screens, verbally repeating pieces of information, and finding patterns or relationships among the numbers, shapes, or colors of multiple cards. Other reported strategies included associating card information with other familiar, real-world objects (reported by eight participants) and using physical motions or gestures as memory aids (reported by three participants). Focusing on the most commonly reported strategy categories, Table 2 provides breakdowns of reported strategies for the spatial and non-spatial conditions, as well as for the landmark and no-landmark conditions. Most notably, these tallies show that a visualization strategy was most often employed when a spatial presentation was used. Figure 6 shows a graphical comparison of the common strategies used for the two presentation styles.

| Strategy | Total | Spatial | | Landmarks | |
|---|---|---|---|---|---|
| | | Yes | No | Yes | No |
| **Visualization** | 19 | 14 | 5 | 9 | 10 |
| **Repetition** | 19 | 8 | 11 | 8 | 11 |
| **Patterns/Relationships** | 17 | 10 | 7 | 7 | 10 |

Table 2. Common strategies used by the participants for the memorization task in Experiment I, broken down by the variables for presentation type and presence of landmarks. Most participants reported using multiple strategies.

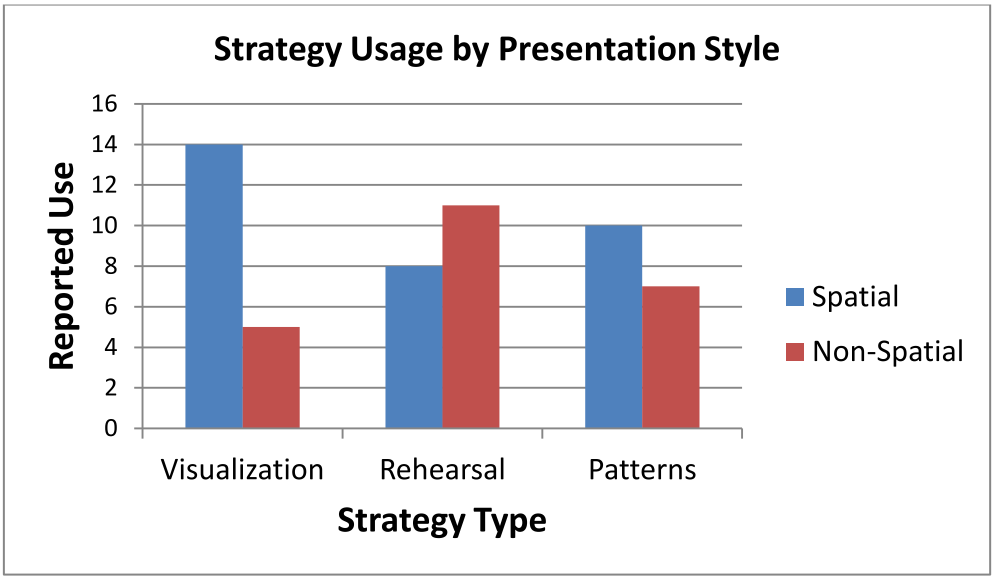


Figure 6. Common participant strategies by presentation style. Significantly more participants used visualization strategies with spatial presentations.

We tested for effects of landmarks and presentation style on visualization strategy with a three-way loglinear analysis, which produced a final model that retained all effects. The likelihood ratio of this model was $\chi^2(0) = 0$ and $p = 1$.

This indicated that the highest-order interaction (between presentation, landmarks, and visualization strategy) was significant, with $\chi^2(1) = 13.46$ and $p < 0.001$.

By looking at Figure 6, it is apparent that, overall, participants used visualization strategies more with spatial presentations than with non-spatial presentations. The real difference, however, was between spatial and non-spatial presentations with landmarks present. With landmarks present, all participants employed visualization strategies in the spatial presentation conditions, but participants never employed visualization strategies with the non-spatial presentation (see Figure 7). With landmarks present, odds ratios indicated that participants were 289 times more likely to use visualization strategies with spatial presentations than with non-spatial presentations, as compared with empty VEs without landmarks, for which odds ratio indicated that participants were no more likely (a ratio of 1.0) to use visualization strategies with spatial presentations than with non-spatial presentations.

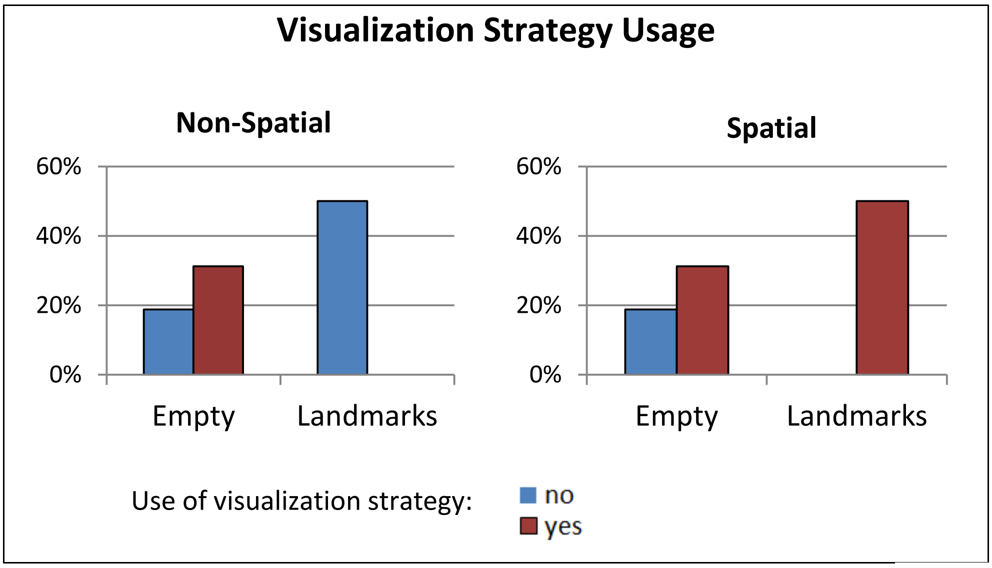


Figure 7. Breakdown of visualization strategy usage by presentation and landmarks. There was a significant interaction between landmarks and presentation style of conditions on the use of visualization learning strategies. With landmarks present, all participants employed visualization strategies in the spatial presentation conditions, but participants never employed visualization strategies with the non-spatial presentation.

Thus, the results of Experiment I show that spatial presentations can not only affect performance in cognitive tasks, but also the strategies used to complete the tasks. Because these effects were observed for a specific and relatively simplistic type of learning task, we decided to perform a follow up experiment with a more complex problem-solving task.

# Experiment II: Problem Solving

Knowledge and recollection of facts form a foundational stage of the learning process, providing a starting point for the deeper levels of understanding that are desired for conceptual learning (Bloom et al. 1956; Krathwohl 2002). Based on this model, since the results of Experiment I show that a spatial presentation can provide benefits for simple factual learning, this supports the claim that spatial presentations may also benefit higher levels understanding. Experiment I provides a strong foundation for studying learning in VEs. The results showed that participants performed better with the spatial presentation method, supporting our hypothesis that spatial techniques can be used to support more efficient memorization; however, it is still unknown whether or not the advantages of a spatial display layout extend beyond simple memorization tasks.

In our second experiment, we moved our investigation beyond memorization, studying the effects of spatial presentation for a cognitive processing task that requires the application of the learned information to solving a problem. This higher level of cognitive processing can be viewed as a more representative example of the type of processing exercised in an educational VE.

## Hypotheses

As in Experiment I, we tested spatial and non-spatial information presentations. We hypothesized that participants would be better able to organize and remember images with the spatial presentation, thus improving performance.

In addition to task performance, we also considered strain on working memory, which can affect the ability to process information (Sweller et al. 1998). Similar to the idea of using external representations to offload mental processing into the world (Norman 1991), we hypothesized that locations could be used offload organizational processing and memory. Thus, we hypothesized that participants would experience lower mental workload with a spatial layout than with the non-spatial representation.

## Task

Rather than simply allowing participants to complete a task by memorizing the presented information, as in Experiment I, Experiment II required participants to discover new information and use it to solve problems. Similar to Experiment I, the purpose of this experiment was to investigate whether spatial presentation affected performance for a task that did not inherently lend itself to benefits from a spatial distribution. To this end, we created a puzzle task that could be presented on cards in either a spatial or non-spatial presentation. The task involved coordinating information from multiple items and required participants to refer back to previously viewed items to make sense of later items. Participants had to use relationships among separate items to deduce new informational rules, which then had to be applied to different situations in the assessment.

To help explain the cards and task, Figure 8 shows a sample set of five cards. Each card is divided into a left area and a right area. The left area contains zero, one, or two squares with symbols or patterns. The right area contains a gray circle on a vertical scale. Figure 8 shows this layout. The vertical position of the circle is determined by what symbol blocks are included on the left. Different symbol blocks correspond to different positive or negative values that will cause the circle to appear in a higher or lower position on the card. The goal of the task is to figure out the effect of each symbol block on the vertical position of the circle.

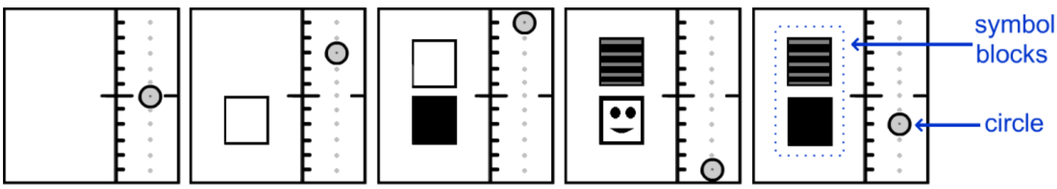


Figure 8. Examples of cards as presented in Experiment 2. In each card, the position of the circle is determined by what symbol blocks are present in the left area.

For instance, Figure 8 shows a sample set of cards as they might be presented in order, one at a time, starting from the left. The leftmost card shows that the circle is in the middle of the scale when no symbol block is present. In the second card from the left in Figure 8, the circle is in a higher position on the card because of the inclusion of the white symbol block. Specifically, the position increases by three ticks on the vertical scale, so the corresponding value is +3. On the third card, the circle is even higher with both a white block and a black block. Because we know the effect of the white block alone, it is possible to figure out the effect of the black block (the black block also corresponds to higher placement, changing the circle's position by +2). The fourth card from the left shows two new blocks: a striped block and a smiley face block. We can see that these cards cause the circle to have a low position on the card, but we cannot determine the exact magnitude of the corresponding values for either block. The fifth card shows the effect of a striped block and a black block together. If we remember the effect of black block, it is now possible to determine the effect of the striped block. In this case, because the black block causes the circle's position to move +2 units, we can figure out that the striped block causes the circle to move -4 movements, explaining why the circle is at the -2 position on the fifth card. By similar logic, if we also remember the previous card with a striped block and a smiley face block, it is now possible to figure out the effect of the smiley face block (-1).

Each trial contained seven cards with different symbols or patterns used for the blocks in each set. That is, no symbol block was reused in multiple sequences. Every card set contained six unique symbol blocks (Figure 9). Of the seven cards in every sequence, two cards contained only one symbol block and four cards contained two blocks. The first card in every sequence was always the card with no symbol blocks and the circle in the middle of the card (the leftmost card of Figure 8).

As in Experiment I, participants viewed the seven cards one at a time in the CAVE. No stereoscopic or head-based rendering was used. In order to prevent potential distortions of the cards' symbol blocks, 3D perspective was not used for the image display. In other words, the cards were displayed flat against the walls of the CAVE.

Before participants started the trials, the card set shown in Figure 8 was used to explain the cards and how to use the information from multiple cards to figure out the effects of all of the symbol blocks. For this familiarization task, participants were not explicitly told that blocks corresponded to numeric values and a script was used to prevent any hints from being provided in the explanation.

Immediately after viewing a sequence of cards twice, participants were tested on their understanding of the effects of the symbol blocks. For this evaluation, participants were presented with cards similar to the previously viewed cards. The evaluation cards, however, did not already have a circle in place on the scale. Participants used a graphical computer application to place the circle in the appropriate position for each card, using a standard optical mouse to click the intended positions. This evaluation was performed for two sets of six cards. In the first set of cards, each card contained a single, unique symbol block. This set of cards tested the ability to figure out the individual effects of the symbol blocks. Cards in the second set contained pairs of blocks, with five of the six cards showing combinations not shown in the previously viewed sequence. This set of cards tested the ability to apply the learned block effects to solve new problems.

Performance was scored based on timing the evaluation and summing errors. Completion time measured the amount of time it took to place all the circles in each card set and then click the "done" button. The error for each card was calculated by taking the difference in magnitude between the correct circle position and the guessed position, with each unit on the scale having a value of one.

We asked participants to rate mental workload using the NASA TLX scale (Hart and Staveland 1988), a standardized test for measuring perceived workload. Participants used the software version of the TLX assessment. Both the circle placement evaluation and the TLX workload evaluation were completed at a desk next to, but not facing, the CAVE.

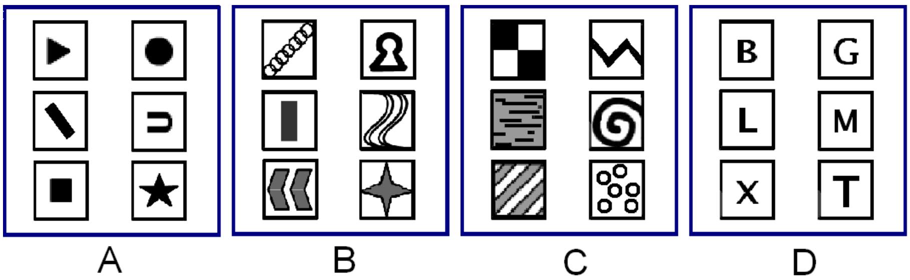


Figure 9. Symbol blocks used in the four card sets of Experiment II. Each card set was composed of one card with no symbol block, two cards with only one symbol block in each, and four cards with two symbol blocks in each.

### Card Set Validity Test

We conducted preliminary testing with different card orders and various types of symbols and patterns in order to develop four card sequences of approximately equal difficulty. We then conducted a validity test of the four sequences to assess any differences in perceived difficulty. For this test, five participants viewed the sequences and completed a circle placement evaluation for a set of six cards, each with a single symbol block. Upon completion of each evaluation, participants were asked to rate the task difficulty on a scale of one to ten, with a rating of ten indicating a very difficult or challenging activity. The results (summarized in Table 3) revealed that the largest difference in mean ratings between any two card sets was 0.8. While participants felt that certain card sets were more or less difficult than others, these differences were not consistent for any particular set. We felt that the results did not show any clear differences in difficulty. Responses in post-test interviews indicate that the differences in difficulties among sets were primarily attributed to individual preferences of the block symbols used. Based on these results, the four sets were considered to be at an approximately equal level of difficulty.

| | **Mean** | **Range** | **SD** |
|---|---|---|---|
| **Set A** | 6.80 | 5 | 1.92 |
| **Set B** | 7.60 | 6 | 2.19 |
| **Set C** | 7.40 | 2 | 0.89 |
| **Set D** | 7.20 | 4 | 1.64 |

Table 3. Perceived levels of difficulty of the four card sets used for the trials based on validity pre-testing

## Experimental Design

Four unique card sequences were used for the trials. The orderings were balanced using a Latin square design. The spatial and non-spatial presentation conditions were controlled within subjects, with each participant completed two trials with spatial presentations and two with non-spatial presentations, alternating between trials. Because the Latin square for card sets yielded four possible orderings that could be done in two ways due to alternating presentation methods, eight distinct orderings were possible from the 2x4 design.

## Participants

Twenty-four university students participated in this experiment (ten were female and balanced across conditions as well as possible). In order to decrease variability of performance differences for our problem-solving task, participation was limited to engineering students between the ages of 18 and 22.

## Procedure

Before beginning, participants first completed a brief questionnaire providing simple background and demographic information. Participants were then walked through the familiarization task using paper cards with the card set shown in Figure 8 (as explained in the Task section). The experimenter read the explanation from a script, asked participants if they understood, and reread sections of the script to help clarify any misinterpretations. Participants were then introduced to the CAVE and the familiarization sequence was displayed according to both the spatial and non-spatial methods (order of these presentations was randomized for this familiarization). Participants were then trained in the use of the card evaluation tool. Finally, the experimenter explained the dimensions of the NASA TLX and trained participants on the use of the workload-rating application.

Participants then completed four trials. For each trial, participants were first shown the set of all possible symbol blocks that would be used in the sequence. The sequence of seven cards was presented twice, with each card displayed for six seconds.

After viewing the sequence in the CAVE, participants immediately walked over to a nearby desk to complete the evaluation tasks. Participants first completed the circle placement evaluation for six cards, each with a single symbol block. Next participants completed the same task for six more cards with two symbol blocks each. Participants then provided workload ratings for the NASA TLX workload evaluation.

The experimenter encouraged participants to rest and take breaks between trials to reduce any effects of fatigue. Participants were required to take a brief two- to three-minute break after completing the first two trials. After completing the four trials and their evaluations, participants completed the dimension comparison task for collecting the NASA TLX dimension weights. Lastly, participants completed an exit interview about strategies used, opinions of task difficulties, and differences between conditions and card sets.

## Results and Discussion

Because the results of Shapiro-Wilk tests of normality for our metrics suggested that the data was not normally distributed, we used a two-way, non-parametric analysis of variance (ANOVA) Friedman test with presentation style and card set as independent variables in order to separately analyze the results for workload, errors for both single and double symbol blocks, and time for both single and double symbol blocks.

We did not find a significant difference between spatial (M = 9.39, SD = 6.93) and non-spatial (M = 8.31, SD = 5.82) presentations for single block errors, with $F(1, 88) = 0.75$ and $d = 0.17$. We found a significant main effect of card set for the single block errors, $F(3, 88) = 4.25$, $p < 0.05$. A post-hoc, Bonferroni-corrected Tukey HSD analysis revealed that card set D (M = 12.33, SD = 7.04) was significantly different from card set B (M = 6.29, SD = 5.43) at the $p = 0.05$ level, with $d = 0.97$.

No significant difference was found between spatial (M = 14.81, SD = 6.97) and non-spatial (M = 13.69, SD = 8.27) presentations for double block errors, with $F(1, 88) = 0.64$ and $d = 0.15$. There was a significant main effect of card set for errors of the double block assessment with $F(3, 88) = 9.04$ and $p < 0.0001$. A post-hoc, Bonferroni-corrected Tukey HSD analyses at the $p = 0.05$ level showed card set D (M = 19.71, SD = 7.46) was significantly different from set B (M = 10.50, SD = 6.53), with $d = 1.32$, and that set D was also significantly different from and set C (M = 11.38, SD = 6.72), with $d = 1.17$.

No significant main effects due to presentation, with $F(1, 88) = 0.01$, or card set, with $F(3, 88) = 1.29$, were found in completion times for single-block assessments. Similarly, no significant main effects due to presentation, with $F(1, 88) = 0.25$, or card set, with $F(3, 88) = 0.55$, were found in completion times for double-block assessments, and no significant differences in workload were found due to either presentation, with $F(1, 88) = 0.37$, or card set, with $F(3, 88) = 1.96$.

Because we found no differences in workload, times, or errors between the spatial and non-spatial conditions, we reject the hypotheses that the spatial information presentation supports improved performance and lower workload for the task. We found no significant interactions between presentation and card set for any of the metrics. We also tested for order effects using a one-way, non-parametric ANOVA (Wilcoxon signed-rank test) at $p < 0.05$. No significant order effects were found for any of the metrics.

Additionally, despite our efforts to develop card sets of equal difficulty, the significant differences between card sets indicate that this was not the case. In general, the time and error results show that card set D was harder than sets B and

C. We suspect that these differences are primarily the result of differences in the ordering of cards with single and double blocks in the presentation sequences. As an example, refer to the sample sequence of Figure 8. It is easy to imagine how the task would be much more difficult if the second card of Figure 8 was presented at the fourth or fifth position in the sequence, rather than at the second position.

Another possibility is that participants were better able to remember and associate the symbol blocks of different sets. The blocks of set D, for example, simply used alphabetic letters instead of shapes or patterns (see Figure 9). While it is possible that performance results were worse for set D due to difficulties working with letters, based on a comparison of the sequences, we feel that it is more likely that the differences can be attributed to the ordering of cards using single and double symbol blocks within the sequences. Interestingly, while performance results for set D were significantly different than B and C, opinions about the difficulty levels for the card sets generally balanced based on the exit interviews. For example, of the 24 participants, seven reported that the sequence using set D was the easiest of the four sets, while seven felt it was the hardest.

## General Discussion

While Experiment I revealed that recall accuracy was higher with a spatial information presentation within a VE, the results of Experiment II do not support the hypothesis that the benefits extend to more complicated learning activities. The task was designed to encourage a critical thinking approach during the information presentation phase. Rather than have participants simply memorize the presented information and then use that information to solve problems, the task required critical thinking in order to deduce the relationships between individual blocks and their effects on the position of the circle. Responses in our exit interviews confirm that this was the approach that all participants employed. It is possible that, although a spatial layout aids performance for simple memorization, no advantage is gained for this type of critical thinking activity.

Another possible explanation is that practice and repetition are needed to learn how to take advantage of additional spatial cues for improved performance. The memorization study provided participants with a practice trial and followed a between subjects design. Thus, participants completed all trials under the same presentation condition. It could be that practice and presentation consistency are necessary in order to develop a successful strategy for taking advantage of the spatial presentation. As Experiment I showed that spatial presentation did significantly affect what strategies were used to complete the task, the within-subjects design of Experiment II may have interfered with participants' strategies. We hypothesize that switching between spatial and non-spatial presentations for each trial made it difficult to effectively use visuospatial strategies for the spatial presentations. In future work, we plan to further investigate the role of intentional spatial strategy usage with spatial information presentations.

Another issue for consideration is the visuospatial nature of the problem-solving task in Experiment II. It has been theorized that humans possess two types of working memory: visuospatial and phonological (Baddeley 1998). The visuospatial memory store is used for images and spatial information. Because the block and circle task involved a high amount of image processing and analysis of spatial relationships, it could have overloaded the visuospatial memory store. The overloaded spatial memory would then be unable to take advantage of the additional organization support offered by the spatial presentation. Past work by Wickens and Liu (Wickens and Liu 1988) suggests that information processing tasks can work in cooperation with each other if they use different memory stores. In contrast to the problem solving activity, participants could rely heavily on the phonological type of memory in the memorization task of the previous experiment. Thus, the memorization task may have left significantly more visuospatial memory available to take advantage of the spatial organization of the wrap-around presentation method. Based on the participants' descriptions of their strategies, we know that many used verbal encodings to remember the symbol blocks; however, we were unable to determine what mental processes or memory types participants were using to organize and relate the pieces of information. A similar study using a simpler critical-thinking task that is more verbal in nature could be used to further investigate this explanation.

An alternative explanation is the need for spatial location to serve as redundant coding of information in order to provide any performance benefits. Past research (e.g., Wickens et al. 2003) has shown benefits of redundant combinations of data presentations. In Experiment I, as well as in other past studies finding benefits to spatial presentation (Hess et al. 1999), spatial position was coupled with other information to be remembered, such as the placement within a sequence or the state of a mechanical system. In the problem-solving task of Experiment II, however, spatial locations were arbitrary and meaningless. It may be worth investigating whether coding redundancy is necessary for performance gains for memorization tasks, and if spatial presentation offers benefits for problem solving activities when location adds informational redundancy.

Our interviews revealed that participants were attempting to deduce either the approximate effects or the exact associated values of the symbol blocks in Experiment II; however, because the symbol blocks could appear in multiple cards, participants were not mapping these effects and values to locations in space. The information that participants were struggling to remember had to be deduced during the trials, and so it was not clearly presented in a spatial layout. As a result, the spatial positions had little meaning in the task. This is clearly in contrast with Experiment I, in which the information that participants were trying to remember was clearly mapped to separate locations in the spatial presentations. In problem solving activities or other tasks in which users must create new information based on existing material, we hypothesize that interactive methods may allow users to give their own meaning to locations. We suspect that educational VR applications could support the creation of informational mappings to space through organizational interactions, annotations, or navigational control.

## Conclusions and Future Work

As VEs support exploratory investigations of virtual systems, engage learners with high levels of interactivity, and enable viewing through multiple, unique perspectives, it has been proposed that VR technology may offer great advantages for educational uses. Immersive VEs allow users to view information relative to their own bodies within the information space and can provide enhanced spatial cues. Further, VEs are able to provide large areas of virtual space to help organize information. The experiments presented in this paper use simplified spatial presentations to investigate if and how users take advantage of spatial mappings in learning tasks. While the results of Experiment I and previous studies, (e.g., Hess et al. 1999), indicate that spatial presentations of information support performance advantages for memorization tasks, spatial layouts afforded no such advantages over non-spatial presentations for our problem solving task. Spatial information presentation alone is not enough to support performance improvements for every task. When using VEs to present information spatially, we feel that it is important to use spatial location to provide meaningful, redundant informational cues when possible—a spatial layout that does not provide redundant coding or useful grouping may provide little benefit. Additionally, the results of Experiment I show that spatial presentation can affect learning strategies, and the results of Experiment II suggest the possibility that consistent strategy usage may be important for taking advantage of spatial presentations. In future work, we plan to further investigate strategy usage with spatial information presentations.

As our two experiments used simple spatial presentations that allowed controlled comparisons between presentation methods, this research leaves several questions for future work. The completed experiments have focused on the presentation of information at different locations in physical space, relative to a fixed position, but real VEs usually have larger environments with more virtual space than can be viewed within a single vantage point. Thus, future research will consider the effects of laying out information at different locations in virtual space, which requires some form of navigation to access all locations.

In addition to designing the presentation of information in space, many related questions remain involving the use of spatial components to aid learning in VEs. For example, we conducted our two experiments in a surround-screen CAVE in order to increase the spatial variance of information positions and allow viewing using only physical rotation. It would be interesting to study whether similar results would be observed with smaller displays. It is possible that the proprioceptive cues provided by the physical rotation helped participants to build mental maps of where information was located, but it could also be the case that the required rotation simply added to the difficulty of the task, making it more difficult to refer back to other locations without losing sight of the current item. This issue could be important for larger VEs, in which the virtual locations cannot always be accessed with physical navigation. Of further interest may be an investigation of how different types of navigation affect the ability to positional mappings to support learning. As more immersive VR systems often allow more physical forms of interaction, and previous work has shown that these more “natural” navigation techniques provide benefits for understanding spatial environments  (Chance et al. 1998; Waller et al. 1998), such navigation techniques could also influence cognitive processing with spatial information layouts. Research by Zanbaka et al. (2004) provided evidence supporting this hypothesis. Zanbaka et al. evaluated performance on a task involving the recollection, comprehension, and synthesis of information in a VE. Comparing performance differences due to the navigation technique used, the study found that real, physical walking provided better performance than the other navigation techniques (such as joystick navigation).

As another issue, while our research found some benefits of the use of space in viewing automated presentations of information, it is possible that interactive methods could be used to establish stronger spatial indexing, thus strengthening the benefit of VR's spatial advantages. Thus, we plan to test differences in the use space between automated and interactive learning environments. Additionally, while Experiment I tested for effects of arbitrary landmarks, future investigations could consider the use of more meaningful, specifically designed landmarks, or perhaps the use of organizing locations to group related information.

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