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Walking through doorways causes forgetting: Situation models and experienced space

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We investigated the ability of people to retrieve information about objects as they moved through rooms in a virtual space. People were probed with object names that were either associated with the person (i.e., carried) or dissociated from the person (i.e., just set down). Also, people either did or did not shift spatial regions (i.e., go to a new room). Information about objects was less accessible when the objects were dissociated from the person. Furthermore, information about an object was also less available when there was a spatial shift. However, the spatial shift had a larger effect on memory for the currently associated object. These data are interpreted as being more supportive of a situation model explanation, following on work using narratives and film. Simpler memory-based accounts that do not take into account the context in which a person is embedded cannot adequately account for the results.

The aim of this research is to understand how movement through space affects one's ability to access information about objects with which one has recently interacted. This assessment was done from a situation model perspective (Johnson-Laird, 1983; van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998). Situation models are mental representations that act as mental simulations that capture the functional relations among the entities in an event. It is clear that as people operate in the world, they are trying to comprehend and understand what is going on around them. Part of this process consists in monitoring changes in space and how these changes influence the availability of other information about the situation. Thus, we should be able to extend situation model theory beyond text comprehension or the viewing of films to this set of circumstances as well. We used a strategy of taking what we know from situation model research in language and film, and applied it to a situation in which a person is interacting with a virtual world.

One classic finding regarding situation models and spatial information was reported by Glenberg, Meyer, and Lindem (1987; see also Radvansky, Copeland, Berish, & Dijkstra, 2003; Radvansky, Copeland, & Zwaan, 2003). In this study, people were presented with brief narratives to read in which an object was either associated with or dissociated from a protagonist, and then the protagonist moved to a new location. For example, a story protagonist could either put on a sweatshirt (associated) or take it off (dissociated) and then go running. After the critical object was associated or dissociated, its identity was probed for, using explicit measures such as memory probes and the ability to answer comprehension questions about the object, as well as implicit measures such as reading times for critical anaphoric sentences. Regardless of the measure used, information about the critical object was less available when it was dissociated than when it was associated.

This pattern reflects the general finding in the situation model literature that cognitive processing is disrupted by spatial shifts as people update their situation models. For example, people read more slowly when they encounter a spatial shift in a text (Zwaan, Magliano, & Graesser, 1995; Zwaan, Radvansky, Hilliard, & Curiel, 1998), take longer to retrieve information about an object the farther away it is (Curiel & Radvansky, 2002; Morrow, Greenspan, & Bower, 1987; Rinck & Bower, 1995), and organize information by spatial regions (Radvansky, 1998, 1999; Radvansky, Spieler, & Zacks, 1993; Radvansky & Zacks, 1991; Zwaan, Langston, & Graesser, 1995), even when the situations are in narrative films (Magliano, Miller, & Zwaan, 2001).

Thus, when people are actively interacting in a situation, even if not reading about one or viewing one in a narrative film, it is plausible to assume that their ability to access information will be affected by any shifts that they

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have made. This is because spatial shifts require people to update their understanding of the current situation. They need either to create a new situation model, or to drastically alter the one that they are currently working with.

Alternative Views

This said, however, a number of alternative views would suggest that people may not be affected by spatial shifts that they themselves experience, as would be the case in a virtual environment. First, although spatial shift effects have been observed in narrative comprehension, it is not unusual for these effects to fail to emerge (Radvansky & Copeland, 2000; Zwaan, Magliano, & Graesser, 1995; Zwaan et al., 1998; Zwaan & van Oostendorp, 1993). This can occur when the space is relatively unknown or is not emphasized by the text or the task. The absence of a spatial shift effect may occur because tracking spatial changes in a text is too difficult, and so people do not closely monitor everything that is taking place. That said, however, work with narrative film, in which spatial shifts are much more dramatic and more akin to the spatial shifts that would be experienced, shows very large and clear spatial shift effects (e.g., Magliano et al., 2001).

A second view is that when people are actually in a situation, because everything is readily available in the environment, updating space may be easy. The working memory load would be much lower than it would be in language comprehension. Thus, we might not observe an updating effect because people are so facile at this sort of task.

A third possibility is that the results observed will conform to standard findings and theories of verbal memory that have been uncovered over the years, showing effects such as encoding specificity, recency, and so forth, and that the interaction with an ongoing situation nominally unrelated to the task at hand will have little influence.

The Present Experiments

With these ideas in mind, we performed a series of experiments to assess whether shifts in experienced space cause processing difficulties similar to those seen in language comprehension, or whether experienced space is processed differently than what has been observed in language processing. On this point, we have already reported some work showing that shifts in experienced space can affect performance (Copeland, Magliano, & Radvansky, 2006; Magliano, Radvansky, & Copeland, in press). For example, when people play a video game from a first person perspective, shifts in space can be accompanied by decrements in performance, such as hitting enemy targets. However, these previous studies have not directly probed for the contents of memory in these ongoing situations.

The experimental task for the present study was loosely based on the design of the Glenberg et al. (1987) study described earlier. Specifically, we had people move through a space, pick an object up in one room, move to the next room, set it down, pick up the next object, move to the next room, and so on. At various points during this process, people were given object name probes with the task of indicating whether the probe was an object they were currently carrying (associated condition), had just set down (dissociated condition), or was some other object. People were told to respond "yes" to associated and dissociated probes, but "no" to all other probes. Thus, at any given point in time, people needed to remember only two objects: the one that they were currently carrying and the one that they had just set down.

Our expectation was that, if experienced situations are mentally represented and processed like those that are read about or viewed, people would be faster and more accurate to respond in the associated condition than in the dissociated condition. However, if this finding is limited to characteristics of verbal processing and memory, and interacting with an environment does not influence verbal memory for the names of objects, then no such difference would be observed.

Because it is impractical to have people actually move through a well-designed large space, and because real spaces do not afford the flexibility and control that one would like to have in an experiment, we had people move through virtual spaces on a computer. There has been a blossoming of research using virtual reality to test ideas about cognition. Much foundational work has shown that the mental representation and processing of virtual spaces results in performance that is essentially identical to that for real spaces (e.g., Sun, Chan, & Campos, 2004) or with only small deviations (e.g., Waller, Loomis, & Haun, 2004). Thus, we expected that the experience of moving through our virtual spaces would be very similar to that of moving through a real space, with similar cognitive consequences.

EXPERIMENT 1

The aim of Experiment 1 was to assess whether the availability of entity information would differ as a function of whether that entity continued to be associated with a person after a spatial shift or was dissociated from the person prior to that shift. Of particular interest was whether these previously observed effects, similar to those observed in text comprehension, would also be observed in a desktop virtual reality environment, as predicted by situation model theory. The alternative is that spatial shifts of this sort would not have an influence on entity availability in short-term memory, as would be predicted by more traditional models of memory.

Method

Participants. Forty-one people (15 female) were recruited from the University of Notre Dame subject pool and given partial course credit for their participation. The data from an additional 10 participants were lost; 5 failed to follow instructions (they responded "no" to dissociated probes), 4 were dropped because of a programming error, and 1 stopped early because of motion sickness.

Materials and Apparatus. The virtual spaces were created with the Valve Hammer environment creation program. This program is used to create environments for the Half-Life video game. The virtual space was a 66-room environment in which all of the rooms were of the same size. Included in each room was a rectangular table along one wall. On one end of the table was the object that the participant was to pick up. There was also an empty part of the table, where the object carried by the participant from the previous room was to be set down. Each room had a different pattern on the walls, to emphasize changes in location. Furthermore, the two doorways in the room were never on the same wall.

The objects were made by combining colors and shapes. The colors were red, orange, yellow, green, blue, purple, white, gray, brown, and black. The objects were all regular geometric shapes: cube, wedge, pole, disk, cross (X), and cone (see Figure 1).

The displays were presented on a 66-in. diagonal rear projection SmartBoard, using a PC-compatible computer.

Procedure. After signing an informed consent form, people were seated about 1 m in front of the large display screen. They were told that their task was to pick up an object from one room, go to the next room, place the object on the empty part of the table, then pick up the next object, proceed to the next room, and so forth. When an object was picked up, it disappeared from the screen. Thus, a person could not see the object that he/she was currently carrying. When it was dropped off, it appeared on the table. Picking up and putting down objects was done simply by touching the appropriate end of the table. It did not matter which action (i.e., picking up or putting down) occurred first.

To make sure that participants progressed through the rooms in the required order, after a person entered a room, the door behind the person closed. The door to the next room did not open until the person both placed the object down on the table and picked up the new object. The doorway to the next room always required the person to turn away from the table in the current room.

There were 51 memory probe trials. Thus, not every spatial shift was accompanied by a memory probe. For the probe trials, upon entering a room, people were presented with a memory probe that consisted of a color and shape name. This probe appeared in the middle of the screen. Participants were told to respond "yes" if the probe corresponded to either the object that was currently being carried (associated) or the one that had just been set down (dissociated). They were told to respond "no" to all other probes. "Yes" and "no" responses were made by pressing one of two buttons on a computer mouse (the left and right buttons were labeled with a "Y" and "N," respectively) that was held in the right hand. People moved by using the left hand to press the arrow keys. The up, down, left, and right arrow keys moved the person through the virtual environment forward, backward, left, and right, respectively. The negative probes were generated by recombining the object and color name for the associated and dissociated objects. For example, if the associated object was a white cube, and if the dissociated object was a red wedge, a negative probe might be "red cube." Thirteen of the trials were probes for the associated object, 13 were probes for the dissociated object, and 25 were negative probes. The experimental procedure typically lasted from 10 to 15 min.

Results

The response time and error rate data are summarized in Table 1. As can be seen, people responded more quickly and more accurately when the object was associated than when it was dissociated [$F(1,40) = 38.37$, $MS_e = 74{,}679$, $p < .001$, and $F(1,40) = 18.64$, $MS_e = .018$, $p < .001$, for response times and error rates, respectively]. In addition, there was no difference in the pattern of response times between dissociated and negative probes ($F < 1$), but people were more error prone to dissociated probes than to negative probes [$F(1,40) = 13.72$, $MS_e = .027$, $p < .001$], which were no different than the associated probes ($F < 1$).

At this point, we decided to examine this updating effect to determine whether it was a general effect, or whether there were interesting individual differences that could provide some insight into which conditions were being affected to produce our pattern of data. Specifically, we were interested in whether the size of the effect was due to differences in maintaining information about the associated object, or to differences in accessing information about the dissociated object. To this end, we performed a correlation on the size of the updating effect with the response times in the associated and dissociated conditions. We found that there was no relation for the associated condition ($r = -.09$), but there was a strong relation for the dissociated condition ($r = .74$, $p < .001$). Thus, the updating effect reflects a difficulty in accessing information about a dissociated object rather than in maintaining information about the associated object.

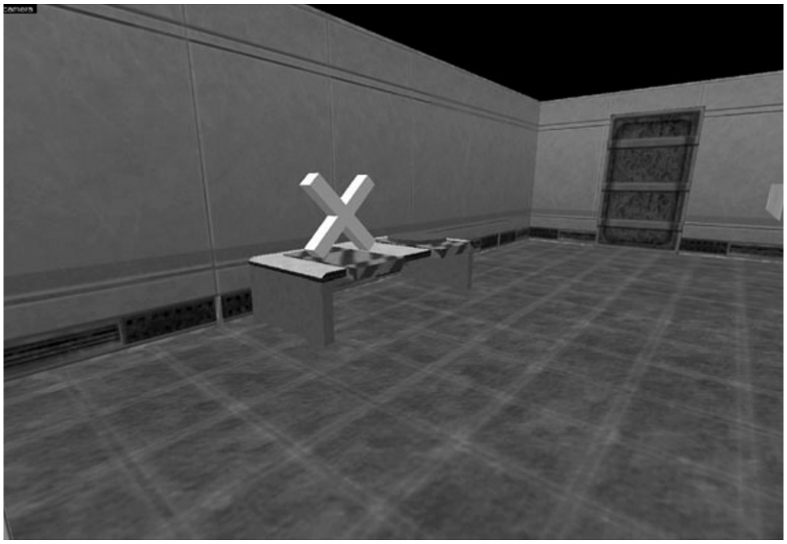

Figure 1. A screen shot from one of the virtual environments.

Table 1
Mean Response Times (RTs, in Milliseconds) and Error Rates (Proportions), With Standard Deviations, for the Three Probe Types, Experiment 1

	RT		Error Rate	
Probe Type	*M*	*SD*	*M*	*SD*
Associated	1,440	330	.20	.14
Dissociated	1,814	484	.33	.18
Negative	1,814	489	.20	.13

Discussion

The results of Experiment 1 illustrate the standard associated/dissociated effect that has been previously observed in the text comprehension literature (Glenberg et al., 1987). Specifically, after a spatial shift, people responded more quickly and accurately when the object continued to be associated with the person than when it had been dissociated. This suggests that people are actively monitoring the spatial and relational characteristics of the dynamic situation, and that this is affecting the availability of information in memory. These results are inconsistent with views of memory that do not take into account how a person is interacting with the environment. Even if people explicitly rehearse the names of the objects, there is a memory disruption.

Although there was a clear effect in Experiment 1, there is some ambiguity as to what was driving it. Specifically, it is unclear to what extent the observed effect was a result of the person monitoring what that person was currently carrying, or to the spatial shift. In situation model theory, the associated/dissociated difference refers to the structural relations of the current situation, whereas the spatial shift refers to the spatial–temporal framework that defines events (e.g., Wyer & Radvansky, 1999). Thus, there are two components, according to situation model theory, that could have been at work here producing this effect.

EXPERIMENT 2

The aim of Experiment 2 was to assess the degree to which the spatial effect observed in Experiment 1 was due to objects' being either associated or dissociated with the person, and/or to a shift in space. That is, these two components need to be broken apart and assessed separately. To this end, Experiment 2 was very similar to Experiment 1, except that sometimes the person walked through a doorway to another room before being probed, whereas for the rest of the time the person walked across a large room toward a second table before being probed. Basically, the large rooms were created by tearing down the walls that divided some of the rooms. In all cases, there were associated and dissociated objects. What varied was whether or not there was a spatial shift, allowing us to separate out the influence of these two factors.

In this experiment, the spatial distance traveled was essentially the same in the shift and no-shift conditions. Although we controlled for this, it should be noted that previous work in narrative comprehension has shown that spatial distance traveled is less important than whether or not a spatial shift has occurred (Rinck, Hähnel, Bower, & Glowalla, 1997). Thus, spatial distance is thought to play a minimal role in such situations.

Method

Participants. Fifty-four people (26 female) were recruited from the University of Notre Dame participants pool and given partial course credit for their participation. The data from an additional 11 participants were dropped. Eight of these people failed to follow the instructions, the data from 1 were lost because of a programming error, and 1 person stopped early after reporting motion sickness.

Materials and Procedure. The virtual spaces were again created with the Valve Hammer environment creation program, using the same apparatus and region creation guidelines. The virtual space for this study included two 53-room environments. Unlike in Experiment 1, some of the rooms were large and some were small. In principle, what we did amounted to removing the walls and doorways separating rooms, thereby keeping distance the same, but varying whether a spatial shift occurred. As in Experiment 1, the walls of different rooms had different patterns, whereas the walls within the same room all had the same pattern.

For the no-shift trials, to direct the person to the correct table, when a person first entered the large room, half of the room was darkened, and there was an invisible barrier that would have prevented people from going to the wrong part of the room with the incorrect table. If the person never tried to cross over to the darkened half of the room, he/she would have never known about the invisible barrier. No one ever reported awareness of the barrier. After the person dropped off the object on the correct table and picked up the next object, the second half of the room was brightened and the invisible barrier was deactivated. On the no-shift trials, a memory probe appeared when the person entered the second half of the room. Again, as on the shift trials, not every instance of crossing to the second half of a room was accompanied by a memory probe.

After signing an informed consent form, participants were seated in front of the display with the same instructions as for Experiment 1. For 15 trials, people did not make a spatial shift (resulting in 5 trials in each condition: associated, dissociated, and negative), and for 36 trials, there was a shift (with 12 trials in each condition: associated, dissociated, and negative). The experimental procedure typically lasted from 10 to 15 min.

Results

The response time and error rate data are summarized in Table 2. The response time and error rate data were submitted to 2 (shift vs. no-shift) × 2 (associated vs. dissociated) repeated measures ANOVAs. For the response time data, there was no main effect of shift ($F < 1$), but there was a significant main effect of associated/dissociated [$F(1,53) = 17.95$, $MS_e = 137{,}022$, $p < .001$], replicating the results of Experiment 1. Importantly, there was a significant interaction [$F(1,53) = 4.33$, $MS_e = 99{,}367$, $p = .04$].

To understand this interaction, we broke the data down in two ways. First, we considered the no-shift and shift conditions separately. Although the size of the associated/dissociated difference was larger for the no-shift (303 msec) than for the shift (124 msec) condition, it was significant for both [$F(1,53) = 14.79$, $MS_e = 167{,}179$, $p < .001$, and $F(1,53) = 6.01$, $MS_e = 69{,}210$, $p = .02$, respectively]. Second, we considered the dissociated and associated conditions separately. Although there was no difference in response time to dissociated probes ($F < 1$), for the associated probes, people took significantly longer (over

Table 2
Mean Response Times (RTs, in Milliseconds) and Error Rates (Proportions), With Standard Deviations, for the Three Probe Types in Shift and No-Shift Conditions, Experiment 2

	No Spatial Shift				Spatial Shift			
	RT		Error Rate		RT		Error Rate	
Probe Type	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Associated	1,433	472	.05	.14	1,588	380	.14	.12
Dissociated	1,736	567	.19	.23	1,682	478	.22	.20
Negative	2,033	614	.10	.19	2,041	561	.15	.15

100 msec) to verify what object they were currently carrying if there had been a spatial shift [$F(1,53) = 6.01$, $MS_e = 69{,}623$, $p = .02$]. Thus, making a spatial shift disrupted processing of currently relevant information.

For the error rate data, there were significant main effects of shift [$F(1,53) = 11.52$, $MS_e = .016$, $p = .001$] and condition [$F(1,53) = 19.71$, $MS_e = .032$, $p < .001$], with people making more errors when there had been a spatial shift and when objects were dissociated from people, respectively. In addition, there was a marginally significant interaction [$F(1,53) = 2.83$, $MS_e = .016$, $p = .09$].

We broke the error rate interaction down as we did the response time data. First, when the no-shift and shift conditions were considered separately, although the size of the associated/dissociated difference was larger for the no-shift (.14) than for the shift (.08) condition, it was significant for both [$F(1,53) = 18.24$, $MS_e = .028$, $p < .001$, and $F(1,53) = 8.26$, $MS_e = .020$, $p = .006$, respectively]. Second, when the dissociated and associated conditions were considered separately, there was no difference in error rates in response to dissociated probes ($F = 1.07$). However, for the associated probes, people made more errors (nearly three times as often) when verifying what they were currently carrying if there had been a spatial shift than if there had not been one [$F(1,53) = 20.99$, $MS_e = .010$, $p < .001$]. Once again, making a spatial shift disrupted processing of currently relevant information. Walking through doorways causes forgetting.

At this point, we again addressed some individual differences in the nature of this updating effect. First, there was no correlation between the size of a person's associated/dissociated and shift effects ($r = -.01$). This suggests that these two effects may reflect qualitatively different processes. Second, for the associated/dissociated effect, as in Experiment 1, there was no relation for the associated condition ($r = -.24$, $p > .10$), but there was a strong relation for the dissociated condition ($r = .59$, $p < .001$). Thus, the associated/dissociated effect reflects more of a difficulty in accessing information about a dissociated object rather than in maintaining information about the associated object. Third, in terms of the shift effect, there was a small relation for the shift condition ($r = .22$, $p = .11$), and a stronger relation for the no-shift condition ($r = -.486$, $p < .001$). Inspection of the scatterplots showed that larger shift effects were due to slower response times in the shift condition, and that smaller shift effects were due to processing difficulties that some people had with the no-shift condition.

Discussion

The results of Experiment 2 replicated the associated/dissociated effect obtained in Experiment 1 and in previous studies (Glenberg et al., 1987; Radvansky & Copeland, 2001; Radvansky, Copeland, et al., 2003), even when there was no spatial shift. Thus, there was an effect of an object's being associated with or dissociated from a person that did not depend on spatial shifts' occurring. Furthermore, there was an effect of making a spatial shift that occurred apart from the associated/dissociated effect. Specifically, there was fairly clear evidence that moving through a doorway from one region to the next made information that would otherwise be highly available less available. Information at a relatively low level of availability was less affected. This shows the different contributions of relational and framework information in situation model processing.

GENERAL DISCUSSION

This work shows that the sorts of situation model updating effects that have been observed in text and film comprehension and memory extend to cognitive processes about actual interactions with other types of situations—in this case, a virtual reality environment. Thus, there appears to be a common set of cognitive processes for dealing with event information, regardless of whether that event is directly or indirectly experienced (e.g., Copeland et al., 2006).

In terms of the associated/dissociated effect, this study was able to replicate findings previously observed only in text processing work (Glenberg et al., 1987; Radvansky & Copeland, 2001; Radvansky, Copeland, et al., 2003). This extends the idea that certain portions of a person's situation model are foregrounded. These foregrounded elements are more available than the other elements. What appears to be guiding this foregrounding process, in terms of spatial relations, is the degree to which there is a functional interaction between the person and the objects in the situation (Radvansky & Copeland, 2000). In this case, carrying an object provides a functional interaction between the person and the object; just having an object in the room that is not being carried does not provide such an interaction.

In terms of the spatial shift effect, we were able to observe a clear influence of changing rooms. This is consistent with previous research on situation models showing that spatial shifts can disrupt processing. Furthermore, the ease with which these effects were observed, in contrast with findings for text comprehension, even in the absence of the need to attend to spatial shifts for the task, suggests that when spatial shift information is readily available in the environment, people are processing this information and incorporating it into their situation models of the world as they move from one place to another.

In some sense, the disruption of cognitive processing is expected. After all, we have repeatedly observed a cost to cognition when spatial shifts occur in text processing. However, in another sense, this result is quite surprising. Because we regularly move through space in our everyday experience, it might be reasonable to expect that we should have become quite facile at dealing with moving from one room to another. However, we did not observe this. Instead, we found that moving through a doorway disrupted cognitive processing. This is made even more surprising by the fact that the memory probe task does not require tracking spatial information at all, and that the greatest memory accuracy deficit of moving through doorways was for objects that a person was currently carrying.

Alternative Explanations

One possible explanation of these results is that this is simply another demonstration of the encoding specificity phenomenon (Thomson & Tulving, 1970). That is, when context changes, memory becomes worse. Although what we report here certainly has some affinity with this classic finding, there are a number of reasons to suspect that this is not the whole story. First, it should be noted that whereas encoding specificity effects are readily found with free recall tasks, they are notoriously difficult to obtain with recognition tasks (Smith, Bjork, & Glenberg, 1978), such as that used here. Second, it should be noted that the currently carried object was in the new context; it was not associated exclusively with the old context. Finally, if what we are reporting were only an encoding specificity effect, it should have been found for both the associated and dissociated objects. However, it was observed primarily for the associated object. Therefore, an encoding specificity explanation of our data comes up short.

Another alternative explanation is that our findings do not reflect situation model processing, but may reflect simpler memory processes, such as those studied in more verbal learning oriented paradigms. Specifically, the present task, in some sense, is a verbal short-term memory task in which a person need only rehearse the names of the two objects and does not need to refer to the ongoing situation. We agree that this is something people could have done. However, the fact that a spatial shift effect was observed with such a small short-term memory load suggests that the structure of the situation is having a profound influence on performance, even on such a simple task. One would expect that in even more complex tasks, the structure of the situation would have a greater impact.

Another idea is that whereas the environment was filled with perceptual/visual/spatial information, the probes were verbal. Thus, there was a mismatch between what people were interacting with and what people were being probed with. However, we would argue that the observation of a spatial shift effect in the presence of such a mismatch also further strengthens our findings. Namely, we found an influence of the experience of a spatial shift disrupting the maintenance of verbal information. This is important in light of popular theories, such as Baddeley's (1986) working memory model, in which verbal and visuospatial information are handled by separate systems. Such a theoretical view might predict that because different types of information are being processed by different aspects of working memory, there should be no influence of the one on the other. However, a clear influence was observed.

A final possibility is that the observed spatial shift effects may actually represent a serial position effect. That is, the associated object was more available because it was more recent. However, this was not the case. Although the associated object was the most recent one in the series of objects, it was not the most recent one seen. That was the dissociated object. In these experiments, a person could not move to the next room until he/she had both picked up the associated object (which disappeared from view) and set down the dissociated object, which appeared on the table in the room. Thus, the last object seen was the dissociated object. Therefore, if there was a serial position advantage, with the most recently encountered object being more available, then there should have been a memory advantage for the dissociated object, not the associated object as was observed in the present experiments.

Situation Model Updating

At this point, we think that the disruption in memory occurs as a result of moving through doorways because entering a new room is a major change in the current situation, and this requires a person to update their situation model of the environment. This is in line with the updating effects observed in research on situation model processing in the domains of text and narrative film comprehension (Curiel & Radvansky, 2002; Magliano et al., 2001; Morrow et al., 1987; Rinck & Bower, 1995; Zwaan et al., 1995; Zwaan et al., 1998). Situation model updating requires a relatively large amount of cognitive effort and coordination, which can slow processing and allow for more errors to occur.

Clearly, more work needs to be done on the effect of changes in space on comprehension and memory. However, the present research provides a tantalizing taste of how considering our interaction with the environment influences our thinking process. That is, we are just beginning to understand how our physical architecture interacts with our cognitive architecture, but we hope to build a more complete understanding as we progress through this line of research.

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