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Spatial Situation Models and Text Comprehension

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Three experiments examined how readers inferred spatial information that was relevant to a story character's movements through a previously memorized layout of a fictional building relative to various tasks. This study also examined how inference measures were related to spatial imagery and reading comprehension ability. Replicating the spatial separation effect reported by Morrow, Greenspan, and Bower (1987), probed objects were responded to faster when they were located in the same room of a building as the main character of a narrative than when the objects were located in different rooms. Experiment 2 ruled out a simple name-based priming explanation of the spatial separation effect, and Experiment 3 demonstrated a facilitation for objects from the character's target room even when readers were provided with a spatially indeterminate list description of the building. The construction-integration model of text comprehension accounted for the spatial separation effect in terms of variations in the knowledge-integration process. It was concluded that the integration of an enriched knowledge network can facilitate the process of mapping text information onto a developing mental representation of a discourse situation, a process that gains further support from spatial imagery and reading comprehension ability.

Many studies have shown that readers infer spatial relations that contain distance information implied by a narrative. For example, in a study by Morrow, Greenspan, and Bower (1987), subjects memorized the floor plan of a building before they read narratives. Each narrative described the actions of a main character moving through the previously studied building. The narratives were interrupted periodically by test words that named two objects. Subjects judged whether the

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two objects were located in the same room or in different rooms of the building. Reaction times to objects from the room which was currently occupied by the main character were faster compared to reaction times to objects from a previously occupied room. Moreover, objects were verified more slowly as the distance between the character's location and the objects increased, suggesting that readers kept track of the character's location during comprehension. Morrow, Bower, and Greenspan (1989) showed that readers focused more on a location that the character was just thinking about (i.e., mental location) than his or her physical location if the mental location was more relevant to the character's actions.

Glenberg, Meyer, and Lindem (1987) asked their subjects to read a series of short narratives each foregrounding a main character by pronominal reference. Each narrative specified an event in which the character and a target object were either spatially associated or dissociated from an object. Faster lexical decision latencies and reading times showed that the target object remained foregrounded when the narrative described a spatial association between the character and the object. Glenberg et al. (1987) claimed that a reader's situation model that controls the foregrounding reflects the spatial structure of events and not just the text structure.

It is tempting to conclude from these results that spatial situation models are always constructed during narrative comprehension. However, other studies have suggested that task characteristics and reader goals can have an impact on how spatial information is incorporated into a situation model. For example, Wilson, Rinck, McNamara, Bower, and Morrow (1993) found that subjects formed detailed situation models only when specific task demands prompted them to focus on location information during reading. In particular, information that was relevant to a character's movements through a building was accessed more rapidly than irrelevant information only when the process of forming a situation model was prompted with test word pairs that named a character plus an object. Similarly, O'Brien and Albrecht (1992) concluded that readers focus on information relevant to a main character's location during narrative comprehension, but this perspective is not adapted unless the characteristics of a text induce such a strategy. Pointing out the dependence of spatial inferences on well-known and easily available information, McKoon and Ratcliff (1992) made a similar claim.

Whereas the studies just discussed used relatively short and determinate narratives, Zwaan and van Oostendorp (1993) used longer and more complex texts to investigate spatial inferences. Subjects read the opening pages of a mystery novel and the instructions and verified spatial inference statements. Subjects who read the text under normal reading instructions had considerable difficulty verifying spatial inferences. Verification accuracy increased when the instruction emphasized the construction of a spatial representation, but only at the expense of substantially increased reading times. However, subjects who read under normal instructions performed well above chance in verifying spatial inferences. This result suggests that, during normal reading, readers do not usually construct a fully integrated but rather an incomplete spatial situation model.

Haenggi, Gernsbacher, and Bolliger (1994) also investigated whether spatial situation models are constructed when subjects are instructed to read stories as they normally do. Subjects read a set of narratives, each of which implied rather than explicitly mentioned a spatial relation among characters and objects. A target sentence which either matched or mismatched that spatial relation always concluded a narrative. The longer reading times for spatially mismatching sentences indicated that readers inferred textually implied information in their mental representations. Another interesting finding of this study was that the reading times were independent of cognitive abilities such as spatial imagery and reading comprehension ability.

The results of these studies provide evidence that readers often update their situation models relative to spatially relevant information during narrative comprehension. However, spatial situation models are not always constructed, and researchers have taken different positions regarding the generation of spatial inferences. Some researchers have argued that spatial information is only inferred in narrative comprehension when task characteristics or stringent instructions encourage subjects to do so (e.g., McKoon & Ratcliff, 1992). Others have suggested that task demands and reader goals play a primary role in the construction of detailed spatial situation models, but a residual and less specific spatial representation can be constructed even when no specific instruction is provided or more complex and longer texts are presented (e.g., Zwaan & van Oostendorp, 1992). We agree with the latter point of view, and would like to add individual differences in cognitive skills as a further source of situation-model construction. To the extent that readers differ in their goals and cognitive skills, the conditions under which readers infer spatial information in their mental representations are expected to vary. For example, the activation of familiar knowledge seems to contribute substantially to comprehension when spatial information is implied rather than explicitly stated in narratives (e.g., Haenggi et al., 1994). In comparison, cognitive abilities might be relatively more important when task characteristics such as the memorization of a spatial layout or testing for spatial information during reading (i.e., probing) support the construction of a spatially coherent situation model (e.g., Morrow et al., 1987).

Thus, there exists a rich empirical literature on spatial inferences in narrative comprehension. The theoretical interpretation of these results always has been in terms of the mental model of the reader. Depending on the precise experimental conditions, the spatial component of the reader's mental model of the text is more or less explicit, resulting in the different sets of results that have been reported. However, an explicit computational account of how such mental models are constructed has not been reported yet.

One goal of this study is to provide such an account in terms of the construction-integration (CI) model of Kintsch (1988, 1992). The mental representations that are constructed according to that model comprise both a text-specific and a situation-specific component. The propositional text base represents the meaning of a text as a hierarchically organized network of propositions. On the situation-model level, readers integrate their previously stored pragmatic, linguistic, and world knowledge with explicit text information to develop an understanding of what a text is about. In this case that situation model consists largely of the spatial information which, as has been shown by the experiments discussed earlier, is crucial for the understanding of these stories. It will be shown that the comprehension mechanisms inherent in the CI model yield a representation of the text that accurately reflects the spatial aspects of the reader's mental model in the task developed by Morrow et al. (1987). The value of such a demonstration is twofold: First, it demonstrates that spatial inferencing can be adequately accounted for by a general computational model of discourse comprehension and does not need special ad hoc mechanisms. Second, the model calculations reveal effects that have not yet been reported in the previous literature.

A second goal of this study is to explore the role of individual differences in spatial and comprehension abilities of subjects in the Morrow et al. (1987) task. This task is particularly suited for our purpose because all texts refer to the same situation, thereby allowing readers to share the same background knowledge about the referent situation. A convergence of results from studies investigating individual differences in inferencing have identified substantial roles of cognitive abilities and domain knowledge in text comprehension. For example, when domain experts were required to read texts about familiar topics, they remembered and inferred more conceptually and causally relevant information compared to domain novices even though both groups were matched in reading comprehension ability (Reutzel & Morgan, 1990; Spilich, Vesonder, Chiesi, & Voss, 1979). Other studies showed that readers who were either high or low in verbal ability but equally knowledgeable in a certain text domain inferred the same kind of information equally often (Schneider, Koerkel, & Weinert, 1990; Yekovich, Walker, Ogle, & Thompson, 1990). In a recent study of reading comprehension ability, Haenggi and Perfetti (1994) found that after knowledge and skill in basic reading processes were accounted for, variations of processes related to inference making were also accounted for. These studies suggest that comprehension includes a continuum of inferential processes which vary to the extent they involve both cognitive abilities and knowledge. The relative contributions of these components to text comprehension depend on many factors such as the text, the domain, and the level of a subject's knowledge. In the study presented here, the reader was provided with background information about the spatial layout of a building. In addition, reading comprehension and spatial imagery abilities were examined as sources of individual differences in constructing and updating a spatial situation model.

The potentially important role of spatial imagery ability in narrative comprehension has not been examined yet. Research by Kosslyn, Brunn, Cave, and Wallach (1984) established that imagery ability represents a variety of relatively independent cognitive skills such as the efficiency of image generation, rotation, and scanning. Poltrock and Brown (1984) examined more specific relations between imagery components and a sample of spatial ability tests. Following Kosslyn et al.'s (1984) methods, they used tasks that were designed to measure different components of imagery. For example, image generation time was measured by presenting short sentences; subjects had to press a response key when they formed the corresponding image. Other tasks were designed to assess mental rotation, integration of image parts, adding details to an image, and image scanning. Poltrock and Brown (1984) found low correlations between the visual imagery tasks, but all spatial ability tests correlated with imagery tasks that required the mental rotation and the integration of image parts. On the other hand, tasks that required image generation and scanning and adding details to images were weakly correlated with the spatial ability tests.

Taken together, these studies on individual differences in mental imagery suggest that several types of spatial processes, such as image generation and transformation processes, can be distinguished. However, these spatial processes are not always easy to separate from each other, and the number of processes involved varies with the difficulty of the spatial task. For the purposes of this study, we distinguish between a simple and a complex type of spatial processing. Complex spatial tasks require the mental manipulation of three-dimensional objects and the storage of intermediate computational results, and as such they reflect spatial transformation processes such as image rotation and integration. In comparison, imagery components like generation and scanning speed of two-dimensional images seem to be weakly correlated with spatial manipulation processes. This might be reflected by relatively simple spatial tasks such as the selection of a sample picture among distractors (Carpenter & Just, 1986). To explore the relative contribution of a simple spatial speed measure to situation-based inferencing, this study included a spatial test that required comparisons between two-dimensional images (i.e., Card Rotation Test). A more complex spatial test involved the mental rotation of cubes and provided a measure of a spatial transformation component (i.e., Cube Comparison Test; French, Ekstrom, & Price, 1963).

The reported studies on individual differences suggest that in addition to specific task demands and reader goals, the availability of cognitive resources such as comprehension and imagery skills can provide an additional source of situation-based inferencing in narrative comprehension. This study explores the potentially important roles of reading comprehension ability and spatial imagery ability in spatial inferencing. Experiment 1 was conducted to replicate and extend the spatial separation effect reported by Morrow et al. (1987): Objects from the same room in which a story character is currently located should be responded to faster than objects from a room that is not occupied by the character. Experiment 2 tested a name-based priming explanation of the spatial separation effect. Experiment 3 addressed the question of whether the speed of establishing a spatial model plays a role in inferencing when subjects are not provided with a spatial layout of a situation. To test this hypothesis, subjects in Experiment 3 memorized a list of rooms and objects names instead of a spatial layout before they read the stories about characters moving around in a building.

Of particular interest was the examination of correlations between response latencies to probed objects and measures of spatial imagery and reading comprehension ability. Such correlations would indicate cognitive processing components that might be involved in updating situation models during narrative comprehension. We can expect the relations among spatial test scores and measures of spatial inferencing during narrative comprehension to vary with the characteristics of both the type of spatial test and the comprehension task. For example, a test that requires the manipulation of objects in space should be related to comprehension when a reader updates a previously established situation model. In contrast, a simpler spatial matching task might be relatively more important than a complex spatial transformation process when a reader is not provided with a spatial layout of a situation. The Card Rotation Test provides a measure of simple spatial matching process, and as such it should be related to the speed of establishing a spatial situation model when the subjects have to generate their own spatial representation.

EXPERIMENT 1

A spatial probe task was used to examine whether readers update spatial information in their situation models while reading stories about characters moving around in different rooms of a castle. According to the spatial separation hypothesis, shorter response times were expected for test words that named objects from the room that the character had just entered. In comparison, response times should increase for test words that named two objects from a room that was not occupied by the character.

Of special interest was the investigation of relationships between response times to test words and reading comprehension as well as spatial imagery ability. To explore the relative roles of image generation and manipulation components in situation-based inferencing, this study included a relatively simple spatial test which required comparisons between two-dimensional images (i.e., Card Rotation Test). A more complex spatial test involved the mental manipulation of cubes (i.e., Cube Comparison Test; French et al., 1963). Subjects relied on a previously memorized spatial layout before they updated a situational representation with respect to a story character's location. Thus, the ability to mentally manipulate these representations might play a more important role in spatial inferencing than a simpler spatial speed measure. This assumption is based on the functional independence of spatial speed and manipulation processes and should reflect itself in a reliable correlation between Cube Comparison Test performance and the time needed to update a situation model with respect to a character's location. We also expected reading comprehension ability to be important since this updating process required the manipulation of a spatial mental representation in memory, which has been identified as a major component of comprehension skill (Cunningham, Stanovich, & Wilson, 1990; Daneman & Carpenter, 1980; Haenggi & Perfetti, 1992). Reading comprehension ability was measured with a modified version of Gernsbacher's Multi-Media Comprehension Battery (Gernsbacher, Varner, & Faust, 1990).

Method

Subjects. Subjects in all three experiments were university undergraduates who were given course credit for their participation; about half of the subjects were women. Forty students from the University of Oregon participated in Experiment 1.

Materials and Procedure. Subjects were tested individually in one session lasting approximately 2 hr. They learned the spatial layout of a castle and read stories about characters moving around in the castle before they completed the reading comprehension, the Card Rotation, and the Cube Comparison Tests. The presentation of the stimuli and the recording of responses for the spatial probe task and the reading comprehension test were monitored by a personal computer.

Spatial Probe Task. Subjects learned the floor plan of a castle from a picture that was 18 × 13 cm in size and showed four rooms with four objects in each room. The floor plan is presented in Figure 1.

Subjects were instructed that they would have to learn the floor plan so well that they would be able to visualize the castle later while reading stories about characters walking through the rooms of the castle. Subjects were given 10 min to memorize the floor plan. During that time, subjects were provided with a master and several blank floor plans to practice naming the four rooms and the 16 objects and placing them in the correct location. After the study period, the master and practice floor plans were collected; subjects had to fill in the room names and the objects in their correct locations on a test plan. When subjects completed the test floor plan they were given 2 min to answer four questions about the spatial layout of the castle.

After memorizing the floor plan, subjects read eight stories, each describing a character moving around in the castle. A sample story is provided in Table 1.

Similar to the materials used by Morrow et al. (1987), each story consisted of 18 sentences and described the actions of a main character, which required them to move through the rooms of the castle. As Table 1 illustrates, the first seven

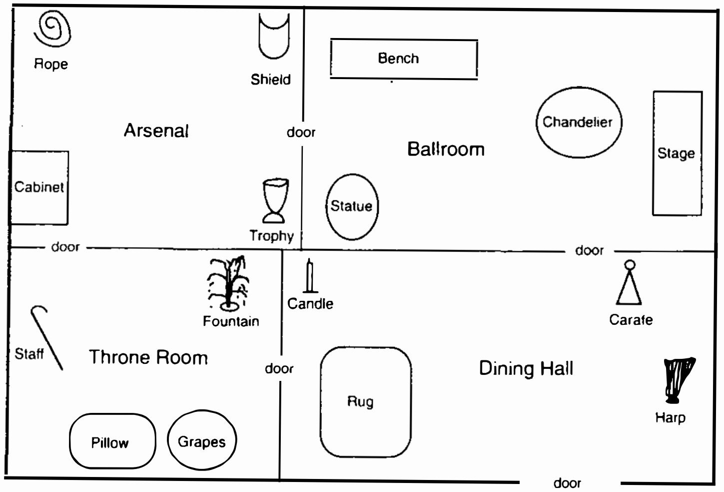

Figure 1. Floor plan of the castle that subjects had to memorize for the spatial inference task in Experiment 1.

TABLE 1
Example Story and Test Words for the Spatial Probe Task Used in Experiments 1 and 3

Lady Penelope sat in the arsenal contemplating her lot in life. She had always been jealous of her younger sister, the Queen. She felt like she had been cursed with bad luck while her sister was blessed with good. She thought her luck had changed when she fell in love with a Duke. But her bad luck returned and he was turned into a toad by an evil wizard. She was beginning to believe that her sister had a hand in her misfortune. She thought of how she could sabotage tonight's event. *Penelope walked from the arsenal into the ballroom.*
* CARAFE * * RUG * (same-other)

She saw that the servants had started nailing up the decorations. Perhaps she could get the wizard to cast a spell that would cause the nails to fall out. *From the ballroom she walked into the dining hall.*
* SHIELD * * HARP * (different)

There she found the wizard eating his lunch. She asked the wizard for the spell, but he refused. *She stomped off to the throne room from the dining hall.*
* PENELOPE * * CANDLE * (different-character)

When she saw the Queen in her throne she decided to try a different approach. She sweetly offered to help her sister dress for the evening. *Satisfied, she walked from the throne room to the arsenal.*
* ROPE * * CABINET * (same-goal)

Now, she thought of how to rig the Queen's gown so that at the perfect moment, the train would fall off.

sentences introduced the character. The second part of each story contained four motion sentences, each of which described a character's movement from a source room to an adjacent goal room. Three motion sentences were followed by two sentences specifying a character's actions in a goal room, and the fourth motion sentence was followed by a sentence that concluded the story.

Two test words naming either two objects or an object and a character followed each motion sentence. Same-goal test words named two objects from the same room that the character had just entered. Same-other test words referred to two objects from the same room, but the room was not currently occupied by the main character. Word pairs naming two objects from different rooms (different-room test words) were also included, and a few character-object test words were also included. When a pair of test words named two objects, subjects had to decide whether the two objects were in the same room. For test words that named an object and a character, the corresponding decision was whether the object and the character were located in the same or in different rooms.

Two material sets were constructed to vary the presentation order of the test words. Word pairs that were used as same-goal test words in the first set were presented as same-other test words in the second set and vice versa, and an object could only serve as a test word once per story. Each subject had to respond to 8 same-goal, 8 same-other, 4 character-object, and 12 different-room test words.

Each story was preceded by a *READY?* signal that appeared in the middle of the computer screen. When subjects pressed a response key, the *READY?* signal disappeared and they read each story from the middle of the screen, one sentence at a time, at their own pace. Subjects pressed keys labeled *same* and *different* to indicate whether two test words named an object pair from the same room as the story character or, in the case of character-object test words, whether a character and object were located in the same room. The test words were presented in capital letters surrounded by asterisks and appeared in the middle of the screen. Subjects were instructed to respond to the test words as quickly as possible without making mistakes. A practice story preceded the eight experimental stories. Subjects needed about 30 min to read the stories and respond to the test words. Response time and accuracy were recorded as the dependent variables.

Reading Comprehension Test. Reading comprehension ability was assessed with a modified version of Gernsbacher's Multi-Media Comprehension Battery (Gernsbacher & Varner, 1988), a measure which is related to the ability to construct a coherent and accessible mental representation (Gernsbacher et al., 1990). The modified version of the Multi-Media Comprehension Battery comprised three narratives which were each followed by 12 multiple-choice comprehension questions. These questions covered explicit as well as implicit information.

The three narratives were 636, 585, and 958 words long, respectively, and all were presented at a rate of 175 words/min on a computer screen. The text appeared cumulatively for each line until the screen was filled. Then, the screen was erased before the next screen of text began to appear. Following each narrative, 12 comprehension questions appeared on the screen one at a time, and subjects were allocated 20 s to select one of five alternatives by pressing a key. When subjects answered a question before 20 s elapsed, they pressed a key to get the next question. Completion time of the reading comprehension test was approximately 30 min.

Spatial Imagery Tests. Spatial imagery ability was assessed with the Card Rotation and the Cube Comparison Tests (French et al., 1963). Both tests load on a spatial orientation factor that can be described as the ability to perceive spatial patterns or maintain orientation with respect to objects in space. Studies of individual differences in imagery suggest that the Cube Comparison Test involves spatial manipulations and the storage of intermediate computational results, whereas the Card Rotation Test provides a measure of a simpler spatial matching process that could be related to image generation or scanning speed (Carpenter & Just, 1986; Poltrock & Agnoli, 1986).

A Card Rotation Test item required the comparison of one drawing of a card with six different drawings of the same card. These six drawings showed the same card either rotated by different angles or turned over, and subjects indicated whether the cards were turned over. A Cube Comparison Test item consisted of two drawings of a cube, and subjects decided whether an item represented two drawings of the same cube. Each of the three sides of each cube showed a different symbol, and no cube had two sides alike.

Subjects completed the Card Rotation Test first, followed by the Cube Comparison Test. The time allocated to complete each test was 8 and 6 min, respectively, and the instructions emphasized speed and accuracy equally.

Results

Subjects took an average 2,798 ms to respond to test words pairing a character with an object, and the mean response accuracy for these words was 91%. As for test words that named two objects, response times for same- (M = 2,445 ms) and different-room pairs (M = 2,400 ms) did not differ significantly, $|t| < 1$.

Because we were most interested in the correct responses to same-room test words, analyses of variance (ANOVAs) were conducted for these data. The mean response accuracy for same-room test words was 89%. Then, the measures of reading comprehension and spatial imagery ability were entered in a regression analysis on the response latencies.

An analysis of correct response times to same-goal and same-other test words was consistent with Morrow et al.'s (1987) spatial separation hypothesis and indicated shorter response times for test words that named two objects from the same room when this room was currently occupied by a main character. This effect was significant, both when subjects, $F(1, 39) = 35.58$, $p < .001$, and test words, $F(1, 7) = 21.65$, $p < .01$, were considered random effects. The mean response times for same-goal and same-other test words are displayed in Table 2.

TABLE 2
Mean Response Times[a] (and Standard Deviations) and Simulated Activation Strength Values for Same-Goal and Same-Other Test Words Across the Three Experiments

	Experiment		
Test Word Type	**1**	**2**	**3**
Response Time			
Same-Goal	2,108 (554)	2,322 (767)	2,866 (869)
Same-Other	2,782 (1.014)	2,868 (809)	3,434 (1,080)
Activation Strength			
Same-Goal	.25	.25	.23
Same-Other	.12	14	.15

[a] In ms.

In a further analysis, the relative contributions of the reading comprehension and spatial test measures to inference latency was examined by stepwise regressions. The comprehension and spatial test measures were entered according to their F values to predict the response times for same-goal and same-other test words. The correlations between response times and the predictors are presented in Table 3.

Table 3 displays substantial correlations between the response times for same-goal and same-other test words, $r(38) < .32$, $p < .05$. Furthermore, the mean response time for each of the two test word types was significantly related to both

TABLE 3
Correlations of Reaction Times for Same-Goal and Same-Other Test Words With the Card Rotation, the Cube Comparison, and the Reading Comprehension Tests (Comp Battery) in Experiment 1

Measures	**1**	**2**	**3**	**4**	**5**
Same-Goal	—				
Same-Other	.73*	—			
Card Test	−.12	.10	—		
Cube Test	−.64*	−.52*	.34*	—	
Comp Battery	−.51*	−.44*	.02	.46*	—

Note. N = 40.
*$p < .05$, two-tailed.

reading comprehension and Cube Comparison, but not to Card Rotation Test performance. Cube Comparison Test performance was also related to reading comprehension ability, and the spatial tests correlated significantly.

Two stepwise regressions were performed using response times for same-goal and same-other test words as separate dependent variables. When the three measures of individual differences were entered into a regression to predict response times for same-goal test words, we found 46.9% of the variance explained. Cube Comparison Test performance entered first and explained 40.7% ($p < .001$) of variance. The reading comprehension measure entered in a second step and accounted for an additional 5.8% ($p < .05$) of variance. Card Rotation Test performance did not contribute significantly to response time for same-goal test words.

The significance of each predictor variable was further evaluated by partialling out the effects of the other two variables. When Cube Comparison and Card Rotation Test performance were partialled out, the correlations between the reading comprehension measure and response times to same-goal test words became nonsignificant ($r = -.30$). In comparison, Cube Comparison Test performance remained significantly correlated with both response measures when comprehension ability and the Card Rotation Test measure were partialled out ($r = -.52$).

When response latency for same-other test words served as the dependent variable, Cube Comparison Test performance entered first and accounted for 27.4% of the variance ($p < .001$). Card Rotation Test performance explained an additional 8.4% ($p < .05$) of variance in response time, and the reading comprehension measure was not a significant predictor. Cube Comparison performance was the only variable that correlated significantly with response time when the effects of the two other predictors were partialled out ($r = -.48$). In contrast, the correlation between the reading comprehension measure and response time became nonsignificant when Cube Comparison and Card Rotation Test performance were partialled out ($r = -.23$). These partial correlations suggest that Cube Comparison Test performance shared a substantial amount of variance in response time to test words. When Cube Comparison Test performance was accounted for, reading comprehension ability was only weakly related to response time.

Discussion

The spatial separation effect found by Morrow et al. (1987) was replicated in Experiment 1: Response times to test words that named object pairs from the same room were shorter when this room was currently occupied by the main character, and response times increased when the character was not in the same room as an object pair. Moreover, correlational analyses identified the ability to maintain orientation relative to three-dimensional objects as a significant predictor of test word-response time.

However, an alternative explanation of the spatial separation effect must be considered here. It could be argued that the response times for same-goal test words are facilitated because they benefit from a name-based priming effect rather than forming a spatial situation model. Unlike same-other test words, only same-goal words are preceded by an explicit statement of the target room (in the narrative). If a room name can prime the objects it contains, then the reaction-time difference between same-goal and same-other test words could partly reflect name-based priming instead of situation-based inferences. This hypothesis was tested in Experiment 2.

EXPERIMENT 2

This experiment was conducted to rule out the name-based priming explanation of the spatial separation effect. A spatial probe task was used again, but unlike the materials in the previous experiment, the motion sentences presented in this experiment never stated a target room explicitly. Each motion sentence named only the source room, and the target room was always referred to as "the next room" (i.e., "Penelope walked from the arsenal into the next room"). If the name-based priming hypothesis is accurate, the facilitation of same-goal over same-other room test words should disappear because both test word types are equally accessible. On the other hand, if same-goal test words are still responded to faster (even though the room names are not referred to explicitly), the name-based priming hypothesis could not account for the data, and the situation-based inference explanation would be supported.

Method

Subjects. Subjects in Experiment 2 were 40 University of Colorado undergraduates from the Department of Psychology subject pool.

Materials and Procedure. Experiment 2 was conducted in a 1-hr session. Similar to the procedure outlined for Experiment 1, subjects memorized the floor plan of a castle before they read short stories about characters moving around the castle. The original floor plan was transformed into a linear version in which the rooms of the castle were arranged from left to right in the following order: arsenal, ballroom, throne room, dining hall. Figure 2 presents the linear version of the floor plan.

Subjects read an adapted version of the story set used in Experiment 1. Unlike the motion sentences used in the previous experiment, only the source room was named explicitly in each motion sentence, whereas the goal room was referred to simply as "the next room." The character always moved through the castle from left to right, starting his or her journey in the arsenal (e.g., "Penelope walked into the first room"), and ending the journey in the dining hall (e.g., "Satisfied,

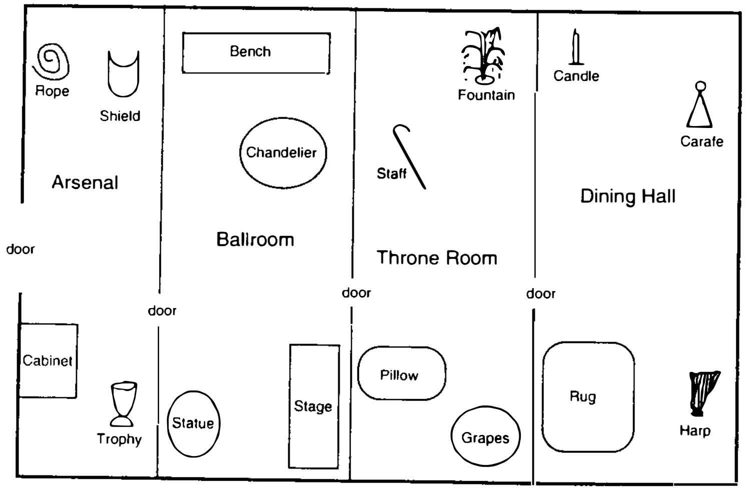

Figure 2. Floor plan of the castle that subjects had to memorize for the spatial inference task in Experiment 2.

she walked from the throne room to the next room"). Each motion sentence was again followed by two test words that named either two objects from the same room in which a story character was located, two objects from a different room than the character, two objects from two different rooms, or a character plus an object.

Results

The mean response time for test words that paired a character with an object was 2,797 ms, and the accuracy rate for these test words was 95.6%. For object test words, response latencies for same- ($M = 2{,}595$ ms) and different-room words ($M = 2{,}492$ ms) did not differ significantly, $|t| < 1.2$.

Of great interest was again the analysis of subjects' responses to test words that named two objects from the same room where the character was located. The mean response accuracy for these test words was 88%. Similar to the results reported previously, subjects took less time to respond to same-room test words when this room was currently occupied by a character versus not. This difference was reliable, both when subjects, $F(1, 39) = 37.60, p < .001$, and target words, $F(1, 7) = 18.39, p < .01$, were considered random effects. The mean response times for same-goal and same-other test words are summarized in Table 2.

Discussion

It should be noted that the transformation of the original two-dimensional floor plan into a linear version simplified the spatial layout. The linear layout version of the text was congruent with the organization of the text, which also described the movements of a character in a linear fashion. Although the change of the spatial layout may have simplified the inference task in Experiment 2, the data indicated a pronounced spatial separation effect in both experiments.

The results of Experiment 2 did not support the name-based priming interpretation of the spatial separation effect: Even when the target room was not explicitly mentioned in a motion sentence, subjects responded 536 msec faster to test words naming two objects from the same room as the character compared to test words referring to object pairs from a room that was not occupied by the character. This result parallels the facilitation effect of 674 msec for same-goal test words reported in Experiment 1, and supports the view that this effect reflects situation-based inferencing more than it reflects simple name-based priming.

EXPERIMENT 3

We argued earlier that the generation speed of images might be relatively more important than spatial transformation processes when a reader is not provided with a spatially determinate description of a situation. To examine this hypothesis, subjects in Experiment 3 memorized a list of the rooms and objects in the castle instead of a spatial layout before they read the stories. Because this list did not provide subjects with a spatially determinate floor plan, the speed of establishing a spatial representation of the building was expected to affect inferencing. Because the Card Rotation Test reflects such a spatial speed measure, it should be reliably correlated with response times to test words that name two objects from the same room. Nevertheless, the spatial separation effect should be equally pronounced in as much as this effect reflects the process of mapping incoming information about a character's location onto a reader's developing mental representation. Once a spatial situation model is established, the ability to foreground this model in the course of comprehension should play a crucial role in inferring spatial information. Therefore, reading comprehension ability was also expected to be related to response time.

Method

Subjects. Another sample of 40 University of Colorado undergraduates from the Department of Psychology subject pool participated in Experiment 3.

Materials and Procedure. Instead of a spatial layout, subjects had to memorize a list that included the four rooms and the 16 objects in the castle before they read the same set of stories and motion sentences presented in Experiment 1. Table 4 illustrates the list of rooms and objects.

Following the spatial probe task, the reading comprehension test, the Card Rotation, and the Cube Comparison Tests were administered according to the procedures outlined earlier.

TABLE 4
List of Room and Object Names That Subjects Had to Memorize for the Spatial Probe Task in Experiment 3

Room	Objects
Arsenal	rope, shield, cabinet, trophy
Ballroom	bench, statue, chandelier, stage
Throne Room	fountain, staff, pillow, grapes
Dining Hall	candle, carafe, rug, harp

Results

The average character-object test word was responded to within 3,597 ms with an accuracy of 88.1%. As far as object test words are concerned, the mean response times for same- (M = 3,150 ms) and different-room test words (M = 3,044 ms) were not significantly different, $|t| < 1.2$.

As in the two previous experiments, the analysis focused on subjects' responses to test words naming two objects from the same room. These test words were responded to with an accuracy of 90%. In a second step, the measures of reading comprehension and spatial imagery ability were again entered in a regression analysis on the response latencies. Similar to the results reported in Experiments 1 and 2, Table 2 displays shorter response times for same-room test words when this room was a target room of a motion sentence. This effect was significant, both when subjects, $F(1, 39) = 41.26$, $p < .001$, and target words, $F(1, 7) = 18.24$, $p < .01$, were considered random effects.

The relative contributions of the reading comprehension and spatial test measures to inference time were again examined by stepwise regressions. Table 5 presents the correlations between response times and the predictors.

As Table 5 illustrates, response times for same-goal and same-other test words were highly correlated. Furthermore, the latency measures for each test-word type were significantly related to both reading comprehension ability and the Card Rotation Test scores, but not to Cube Comparison Test scores. The two spatial tests correlated moderately but were not related to comprehension ability.

The response times for same-goal and same-other test words were used as the dependent variables for two separate stepwise regressions. When the three measures of individual differences were allowed to enter into a regression according to their F values to predict response times for same-goal test words, 38.9% of the variance was explained. Card Rotation Test performance entered first and accounted for 22.9% ($p < .001$) of variance. In a second step, the reading comprehension measure was entered and explained an additional 13% ($p < .05$) of variance. Cube Comparison Test performance did not account for a substantial portion of variance in response time.

TABLE 5
Correlations of Reaction Times for Same-Goal and Same-Other Test Words With the Card Rotation, the Cube Comparison, and the Reading Comprehension Tests (Comp Battery) in Experiment 3

Measures	1	2	3	4	5
Same-Goal	—				
Same-Other	.86*	—			
Card Test	−.48*	−.55*	—		
Cube Test	−.01	−.34*	.43*	—	
Comp Battery	−.43*	−.36*	.15	.23	—

Note. N = 40.
*$p < .05$, two-tailed.

A similar pattern of results was observed when response time for same-other test words was used as the dependent variable: Card Rotation Test performance entered first into the equation and explained 30.7% ($p > .001$) of variance. The reading comprehension measure entered second and accounted for an additional significant portion of variance in response time (7.6%; $p < .05$).

After Card Rotation and Cube Comparison Test performance were partialled out, response times for same-goal and same-other test words were still significantly related to reading comprehension ability ($r = -.40$ and $-.35$, respectively). Similarly, the partial correlations between the two response-time measures and the Card Rotation Test score remained significant when comprehension and Cube Comparison Test performance were partialled out ($r = -.50$ and $-.45$, respectively). These partial correlations demonstrate the roles of Card Rotation and reading comprehension test performance as two substantial sources of variance in inference time.

Discussion

The mean response times to same-room test words were substantially longer in Experiment 3 (3,150 ms) compared to the times measured in Experiments 1 and 2 (2,445 and 2,595 ms, respectively). This result suggests that subjects needed additional time to infer spatially relevant information in their situation models during reading. Because the list of rooms and objects was spatially indeterminate, subjects had to allocate more processing resources to construct a spatial situation model when they were presented with the texts. In contrast, memorizing a spatial layout in the previously presented experiments provided subjects with a spatially determinate situation model that enabled them to do faster inferencing. That subjects did indeed keep spatially relevant information accessible during reading even after they had memorized the spatially indeterminate list was illustrated by a pronounced spatial separation effect: Subjects responded 568 ms faster to two objects from the same room that was currently occupied by a character than they did when the test words named two objects from a room that was not occupied by a character.

It should be noted that the name-based priming argument could also be raised to explain the spatial separation effect reported in Experiment 3. According to this view, subjects memorized a hierarchical list of the four room names, and associated with each room name are the names of four corresponding objects. When a room name is mentioned in a motion sentence, same-goal test words would be responded to faster because the object names associated with those room names are activated. Although we suggest that the data, especially those reported in Experiment 2, reflect situation-based inferences, a name-based priming account cannot be completely ruled out to explain the spatial separation effect in Experiment 3. Reading comprehension ability was a significant predictor of inference time in Experiment 3. This result suggests that the comprehension process used to construct a situation model relies on the ability to focus on spatially relevant information. Moreover, the ability to perceive the configurations of two-dimensional objects was significantly related to test-word response time. This result suggests that individual differences in the speed of establishing a spatial model may play an important role in inferencing when subjects are not provided with a spatially determinate description of a situation.

THE SIMULATION

The data on spatial inferencing in the Morrow et al. (1987) task suggest that readers form a "mental model" based upon the spatial information they are given, and the properties of this model determine their behavior in the spatial probe task. Just what is a mental model, how is it formed, and how do its characteristics affect behavior on the probe task? The answer to these questions depends on how the concept is theoretically elaborated and specified, and therefore, it varies with different theorists.

One theory of discourse comprehension that is sufficiently well-developed to allow detailed modeling is Kintsch's (1988, 1992) construction-integration (CI) model. This theory describes in computational detail how a situation model is formed, what it is like, and how it affects responses on the probe task. The important point in all of this is that it does so without making any special ad hoc assumptions, but it is able to account for this very specialized experimental domain with the same mechanisms that have been used in many other domains—from children's story understanding to learning from scientific texts.

Our goal was not to provide precise quantitative fits to the response-time data, but rather to examine whether the CI model produced a pattern of results that was qualitatively comparable to the data across the three experiments. As in most recent studies (Kintsch, 1992; Kintsch & Welsch, 1991; Otero & Kintsch, 1992), the goal was to establish qualitative correspondence between a minimally constrained model and experimental data.

MODELING THE SPATIAL SEPARATION EFFECT

In what follows, we simulate the spatial separation effect reported here in terms of the CI theory (Kintsch, 1988, 1992; Mross & Roberts, 1992). According to the CI theory, a text representation consists of a propositional text base (derived solely from the text) and the knowledge a reader brings to the text. In order to model the spatial separation effect, each of the 8 same-room motion sentences was coded as a list of propositions that was subsequently extended by adding associated propositions from the prior knowledge net and inferential information (both derived from the floor plan). For each motion sentence, a separate simulation computed the activation strengths for objects from the tested room, and the strength values were averaged over the number of texts to model the facilitation of same-goal over same-other test words.

Figure 3 shows an associative network of propositional elements that was constructed to represent the meaning of a motion sentence (e.g., "Penelope walked from the arsenal into the ballroom") relative to a prior knowledge net in

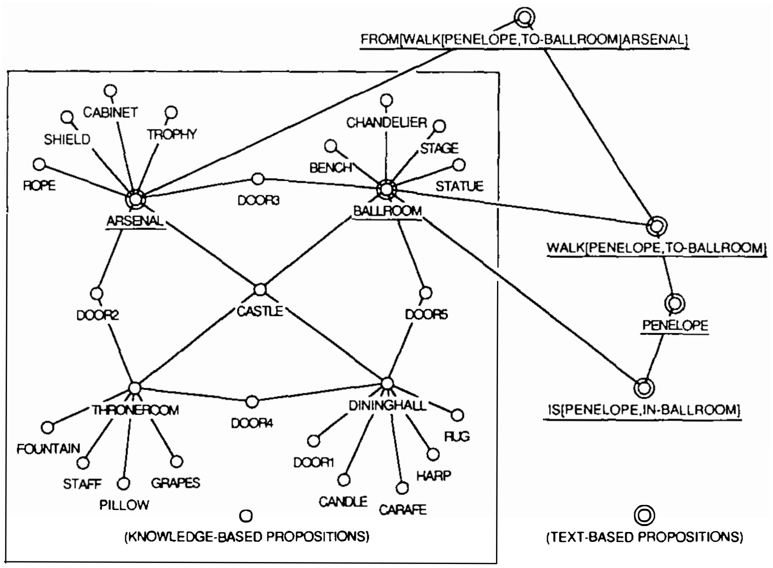

Figure 3. The associative network of propositions generated to simulate the integration of text- and knowledge-based information in Experiment 1. Text-based propositions are underlined, and the frame designates the area of knowledge-based propositions in the network.

Experiment 1. The nodes in the network correspond to propositions that are interconnected when they share the same referent (i.e., argument repetition), and each proposition is linked to itself. The activation pattern flowing through the network is determined by these links and the assigned strength values. In this study, text propositions were assigned link weights and self-strength values of 1. In comparison, the corresponding parameters were set to 0.5 for knowledge-based propositions because they are assumed to have a lower impact on the integration process than text propositions. The set of knowledge-based propositions shown in Figure 3 includes unmentioned room names (e.g., dining hall), object names (e.g., rug, grapes, trophy, statue), and the doors that link the different rooms of the castle. In addition to knowledge- and text-based propositions, the network also contains an inference proposition (i.e., is [Penelope, in-ballroom]). The graph shown in Figure 3 was translated into matrix form yielding a coherence matrix that specifies the link weights of a propositional network.

The comprehension process was simulated by repeatedly multiplying the coherence matrix with the initial activation vector until the network stabilized. The initial values in the activation vector were set to 1 and 0 for text- and knowledge-based propositions, respectively. Following each multiplication, all activation values were divided by the maximum activation value in order to restrict the highest value to 1 (Kintsch, 1992). All propositions in Figure 3 corresponded to a single processing cycle and were integrated simultaneously.

To simulate the spatial separation effect, each of the 16 same-room motion sentences was propositionalized and integrated with the corresponding knowledge network for each of the three experiments. Because the same motion sentences were used in Experiment 1 and 3, the same text-based propositions entered the simulation. As for Experiment 2, two additional propositions (e.g., next room and equal [next room, ballroom]) were added to the network because the goal room was not mentioned in the motion sentences. The prior knowledge nets also differed considerably between the three experiments. In comparison to the net created for Experiment 1 (see Figure 3), the knowledge-based nodes were arranged linearly for the other two experiments. The linear floor plan used in Experiment 2 and the list of rooms and objects presented in Experiment 3 implied a linear arrangement of the four rooms. Furthermore, the knowledge net for Experiment 3 did not specify any doors between the four rooms since no doors were specified on the list. Aside from these variations in the constructed text representations, the same principles were used to simulate the activation values of same-goal versus same-other test words across the three experiments.

Each motion sentence preceding a same-room test word was simulated according to the CI model, and the mean activation values for same-goal and same-other test words were computed for each experiment. If the spatial separation effect can be accounted for with the CI model, then the simulation should produce higher activation values for objects that are located in a target room of a motion sentence. In comparison, the simulated activation values should be relatively lower when a motion sentence prompts objects from a nontarget room. Table 2 shows that the simulation data closely parallel the pattern of results reported for the response-time data across the three experiments.

The simulation results demonstrate that a minimally constrained CI framework can account for the spatial separation effect found in three experiments. Propositions were constructed from a textual input and connected to an associative knowledge net. Then, an activation process was used to deactivate sparsely interconnected nodes and to increase the activation of densely interconnected portions of the network. In focusing the CI model on the spatial separation effect, our goal was to simulate an effect that was equally pronounced across three experiments. In a next step, we examined whether the model would be powerful enough to predict how different portions of the text representation are activated depending on variations in the associative network between experiments.

MODELING THE AVAILABILITY OF NONFOREGROUNDED INFORMATION

The simulation was also used to examine more subtle effects in the response-time data that would have been undetected otherwise. More specifically, the CI model was used to predict the activation strength for nonforegrounded spatial information in a situation model. For each experiment, the activation values for same-other test words were computed relative to the four rooms they referred to. These estimates were then compared with the mean response times to same-other test words measured in the experiments. Again, each of the 8 motion sentences that preceded a same-other test word was entered into the simulation exactly as it was presented to the subjects, but this time the activation values were averaged over each of the four rooms the test words referred to. Each of the four rooms was prompted twice as a same-other room in each experiment.

The CI model implies that the activation strengths for same-other test words should differ between the experiments depending on the room they refer to. For example, the representation of the knowledge net in Experiment 1 suggests that same-other test words should be equally accessible to comprehension for each of the four rooms because all same-other room objects are arranged relatively close to a target room in the knowledge net. In comparison, the linear spatial representation used in Experiment 2 implies that same-other room objects should be less accessible if they are from the arsenal or the dining hall. This is because those rooms are relatively far away from the center of the situation model. A similar pattern of activation strengths for same-other room objects could be expected for Experiment 3 because the list version also implies a linear representation of knowledge nodes.

For each motion sentence that preceded a same-other test word a simulation

TABLE 6
Mean Response Times[a] (and Standard Deviations) and Simulated Activation Strength Values for Same-Other Test Words per Room Type Across the Three Experiments

	Experiment		
Test Word Type	**1**	**2**	**3**
Response Time			
Arsenal	2,733	3,084	3,353
	(1,074)	(962)	(1,064)
Ballroom	2,926	2,698	3,610
	(1, 197)	(782)	(1,248)
Throne Room	2,666	2,653	3,173
	(960)	(2,653)	(1,227)
Dining Hall	2,803	3,037	3,600
	(1,017)	(981)	(1,335)
Activation Strength			
Arsenal	.11	.12	.13
Ballroom	.10	.17	.16
Throne Room	.12	.16	.18
Dining Hall	.14	.09	.13

[a] In ms.

was run and the mean activation strengths were computed for each room separately. The simulation results and the corresponding response latencies are summarized in Table 6.

Confirming our expectation, the simulated activation values for test words referring to same-other room objects were comparable for each room type in Experiment 1. In as much as objects in the ballroom and the throne room received relatively more activation than the remaining two rooms, the simulation data also correspond to our distance hypothesis formulated for Experiment 2. A similar effect could be observed for the simulated activation strengths for same-other room objects in Experiment 3: Objects that referred to a room from the center showed a facilitation effect.

The next step is to examine whether the simulation data correspond to the response-time patterns to test words. As illustrated in Table 6, the response times for same-other test words closely mirror the simulated activation strengths for Experiments 1 and 2. Reflecting the relatively close range of activation strengths reported for Experiment 1, response times for objects from the arsenal, the ballroom, the throne room, and the dining hall did not significantly differ when these rooms were not currently occupied by a character, $t(39) < 1.3$, $p > .2$. The mean response times for same-other test words collected in Experiment 2 also corresponded to the simulation result that rooms from the center of the associative network received more activation: Objects from the ballroom as well as the throne room were responded to faster than objects from both the arsenal and the dining hall, $t(39) = 2.4$ to 2.9, $p < .05$. As for Experiment 3, the simulated activation patterns for same-other test words were only partially comparable to the latency measures. Consistent with the simulated activation strengths, response times were significantly faster for objects from the throne room compared to objects from both the ballroom and the dining hall, $t(39) = 2.71$, $p < .01$. However, the ballroom had higher theoretical activation scores than the arsenal, and the response times showed the opposite trend, $t(39) = 1.4$, $p = .16$. Another inconsistency was that the ballroom and the throne room had higher activation scores than the arsenal and the dining hall, whereas the response times were comparable, $|t| < 1.0$.

In sum, the simulation results demonstrated that the model was able to account for the spatial separation effect reported across three different experiments. Moreover, the CI model was also able to establish a qualitative fit with response-time data that were determined by the specific characteristics of the spatial inference task. Although a qualitative fit between the CI model and the response times for same-other test words was achieved in Experiments 1 and 2, the model did not fit the data very well in Experiment 3. This finding could be attributed to the fact that subjects in Experiment 3 were not provided with a spatially determinate layout. As a consequence, subjects might have shown considerable variations in how they represented the list of rooms and objects, and their representations might have differed from the linear version we used to simulate the activation values in Experiment 3.

GENERAL DISCUSSION

The three experiments reported here indicate that readers draw spatial inferences to update their situation models during comprehension of narrative texts. Replicating the spatial separation effect reported by Morrow et al. (1987), object test words were responded to faster in Experiment 1 when they were located in the same room as the main character of a story than when the objects and the character were located in different rooms. In addition, two control experiments were performed. Because the target room was only explicitly mentioned in the story before the same-goal but not same-other test words, it is possible that the spatial separation effect might be due to the priming of object names via their corresponding room names. For example, if the two test words are from the ballroom, then the sentence "Penelope walked from the arsenal into the ballroom" could partly activate the objects in the ballroom since the target room is explicitly mentioned. Experiment 2 demonstrated an equally pronounced facilitation effect for same-goal test words even when the target rooms were not explicitly mentioned in the motion sentences (e.g., "Penelope walked from the arsenal into the next room"). This result does not support a name-based priming explanation of the spatial separation effect. In Experiment 3, subjects needed relatively more time to incorporate spatial information in their mental representations when they were not provided with a spatially determinate description of a layout, but the magnitude of the spatial separation effect was not affected by this manipulation. Thus, all three experiments suggest that subjects were indeed operating on the basis of genuine spatial situation models. However, the name-based priming account was not totally ruled out and remains to be examined in further research.

How are such situation models constructed? The construction-integration theory of discourse comprehension (Kintsch, 1988, 1992) provides one possible account for this process. It enables us to simulate in detail the comprehension process and compare the results of the simulation with the experimental data. Not only does the simulation yield results that are in good qualitative agreement with the data, it also suggested the existence of secondary effects in the data which had hitherto gone unnoticed: Depending upon the nature of the spatial layout, enhanced facilitation effects were correctly predicted by the model. The most important aspect of these simulations, however, is not their ability to produce predictions consistent with the pattern of the experimental data, but that they do so without requiring any special ad hoc mechanisms. The same model that has been applied to many other tasks involving text comprehension, in one way or another, provides a good account of the present experimental paradigm. The fact that the model constructed here involves an important spatial component does not necessitate a new theory but can be readily incorporated into the existing framework of the CI model.

The Structure Building Framework of Gernsbacher (1990) is in principle compatible with the CI approach, though it directs attention to somewhat different aspects of the comprehension process. According to this framework, incoming text information is mapped on previously stored memory nodes to construct a mental structure. In as much as subsequent information coheres with previous information, the mapping process is facilitated, much as the verification of foregrounded object test words was speeded up. Consequently, when incoming information is less coherent, it becomes more difficult to map onto a mental structure, as was the case when subjects were tested with nonforegrounded objects. The relatively slower response times for same-other test words might reflect the activation of additional knowledge that enables readers to map incoming information (i.e., nonforegrounded object test words) onto their situation models.

In this study, as well as in Morrow et al. (1987), readers constructed detailed spatial models. However, whether they do so or not depends on their goals and the task demands of the experiment (O'Brien & Albrecht, 1992; Wilson et al., 1993). In the CI theory, the construction process is under the control of reader goals and task demands, and just because it is possible to construct a specific spatial model from a given discourse does not mean that readers will always do so. The narratives used in this study referred to the same situation, and the memorization of a spatial layout or a name list allowed readers to share the same background knowledge. This memorization procedure or testing for spatial information might have encouraged subjects to adopt strategies they do not normally use during comprehension of more complex texts that refer to a variety of situations. However, we have already pointed out that spatial situation models, although more residual and less specific, are constructed even when no specific instruction is provided or more complex and longer texts are presented. We choose the Morrow et al. (1987) task for our simulation purposes because it allows a specification of the knowledge base that allowed readers to elaborate the narratives. In the study presented here, it was also important to provide the readers with the same amount of background knowledge in order to examine the relative roles of reading comprehension and spatial imagery abilities in constructing and updating a spatial situation model.

To gain further insight into the processing characteristics of situation-based inferences, correlations between response latencies to test words and measures of cognitive skills were examined. Reading comprehension ability was moderately related to test word-response time indicating that a reader's ability to keep relevant parts of a situation model foregrounded could play an important role in narrative comprehension. This result was relatively independent of the specific constraints of the spatial inference task. In comparison, measures of domain-specific cognitive abilities such as spatial imagery ability were related differently to word-response latency with changing task characteristics. When readers were provided with a spatially determinate layout of a building before they read the narratives, the ability to maintain orientation with respect to three-dimensional objects in space was a significant predictor of test word-response latency. When readers relied on a spatially indeterminate list description of a building to comprehend the narratives, the ability to perceive patterns of two-dimensional objects was relatively more important to spatial inferencing.

In as much as the Card Rotation Test is easy enough to be solved by most people, it reflects the speed of performing a simple spatial matching process rather than the accuracy of more complex spatial operations. In comparison, the more complex Cube Comparison Test involves mental rotation, encoding, and maintenance of intermediate computational results (Carpenter & Just, 1986), and as such, it reflects processes beyond the speed of a spatial matching process. In sum, individual differences in manipulating previously established situation models contributed to the comprehension of spatially relevant information when readers had memorized a spatially determinate layout, whereas the generation speed of a spatially determinate situation model had an impact on comprehension when readers were provided with a spatially indeterminate description of a layout. That different components of spatial imagery ability contributed to the time to respond to test words substantiates the conclusion we based on the spatial separation effect reported earlier, namely that readers use previously acquired knowledge to form a spatially determinate situation model. Readers then update their situation models in the course of comprehension relative to spatial information provided in the text and individual processing resources such as the speed of generating or manipulating a spatial model and the ability to keep relevant parts of the model accessible. To further validate the suggested effects of imagery components on spatial inferencing, further research should include alternative imagery tasks that are specifically correlated with different spatial test measures.

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