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Working memory in developing and applying mental models from spatial descriptions ☆

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Abstract

Four dual-task experiments examined visuospatial, articulatory, and central executive working memory involvement during the development and application of spatial mental models. In Experiments 1 and 2 participants read route and survey spatial descriptions while undertaking one of four secondary tasks targeting working memory components. Converging evidence from map drawing and statement verification tasks indicates that while articulatory mechanisms are involved in processing the language itself, visuospatial and central executive mechanisms are involved in developing spatial mental models, particularly during route description reading. In Experiments 3 and 4 participants undertook the same working memory tasks, but did so during testing; results from memory and secondary task performance converge to demonstrate that using spatial mental models is a visuospatially and centrally demanding process, particularly following route description learning. Taken together, results demonstrate that spatial mental model development and application are contingent upon multiple working memory systems and interact with representational formats.

Keywords: Spatial mental models; Working memory; Discourse processing

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Introduction

Readers construct cohesive mental models of what a text describes, integrating time, space, causality, intention, and person- and object-related information. That is, readers progress beyond the text itself to represent the described situation (Bransford, Barclay, & Franks, 1972; Glenberg, Kruley, & Langston, 1994; Graesser, Millis, & Zwaan, 1997; Johnson-Laird, 1983; van Dijk & Kintsch, 1983; Zwaan, Langston, & Graesser, 1995; Zwaan & Radvansky, 1998). Most work investigating situation models comes from narrative discourse (e.g., Zwaan, Radvansky, Hilliard, & Curiel, 1998; Zwaan et al., 1995). Additional work has examined mental model formation from reading non-spatial and spatial expository texts (Ferguson & Hegarty, 1994; Glenberg & Langston, 1992; Graesser & Bertus, 1998; Lee & Tversky, 2005; Millis, Graesser, & Haberlandt, 1993; Noordzij & Postma, 2005; Perrig & Kintsch, 1985; Taylor & Tversky, 1992a). Whereas both narrative and exposi-

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tory texts lead to mental model development, it is unclear which working memory mechanisms are responsible for constructing these mental representations and when they may play a role (i.e., de Vega, 1995; Radvansky & Copeland, 2001, 2004a, 2004b, 2006a, 2006b; Zwaan & Radvansky, 1998). The present experiments examine this question with spatial descriptions and investigate working memory mechanisms (visuospatial, phonological, central executive; Baddeley, 1992, 2002) involved in mental model formation during reading, and mental model application at test.

Mental models and spatial descriptions

The Event Indexing model (Zwaan et al., 1995) proposes that discourse events are indexed along at least five dimensions (temporal, spatial, causal, intentionality, agent- and object-based features) and that each plays a role in comprehension. Situation models (i.e., Glenberg et al., 1994; Graesser et al., 1997; Johnson-Laird, 1983; van Dijk & Kintsch, 1983) are built from interactions amongst these indexes. Recent extensions of the model propose four classes of processes operating on these representations: construction, updating, retrieval, and foregrounding (Zwaan & Radvansky, 1998). Construction involves building a situation model during comprehension, updating is modifying existing models with new information, retrieval is extracting information from models, and foregrounding is maintenance of model information in working memory. The Resonance Model (Myers & O'Brien, 1998; O'Brien & Myers, 1999), in contrast, argues that mental model construction is mediated by the automatic resonance of discourse-level to sentence-level relations, and that updating involves the interplay between these two levels, resulting in differential item interrelatedness in memory. Resonance theory maintains that retrieval varies as a function of this interrelatedness (see also the C-I model, Kintsch, 1988, and the Landscape Model, Linderholm, Virtue, Tzeng, & van den Broek, 2004). The present work focuses on the working memory processes involved during construction and retrieval of situation models during spatial description reading and testing. Constructivist situation model theory predicts active working memory involvement in tracking multiple text dimensions (i.e., Kintsch, 1988; Zwaan & Radvansky, 1998), while network-based theory (i.e., Myers & O'Brien, 1998) predicts less differential working memory involvement in the activation and linking of current and existing contextual features of a discourse.

Spatial descriptions convey geographical information through language, and generally adopt a particular perspective. Survey descriptions represent space from an allocentric ("birds-eye") perspective, use an extrinsic reference frame (i.e., no implied viewer), and convey directions in cardinal terms (i.e., *north, south, east, west*). In contrast, route descriptions typically represent space from an egocentric ("first-person") perspective, use an intrinsic reference frame (e.g., *in front of you, to your right, to your left*), and convey information regarding relevant landmarks, turn sequences, and travel distances (Levelt, 1982; Taylor & Tversky, 1992b). Both perspectives are commonly used, for instance, when giving directions or describing an environment's layout.

Spatial descriptions are quite effective at conveying spatial information. Taylor and Tversky (1992a) found that mental models derived from both route and survey spatial descriptions were similar to those acquired during map study: after studying each, participants were equally adept at sketching maps and verifying inference statements. It appears that participants were able to develop spatial mental models that are not inextricably tied to the learned perspective (see also Brunyé & Taylor, 2007; Ferguson & Hegarty, 1994; Lee & Tversky, 2005; Noordzij & Postma, 2005). In contrast, some recent work shows that spatial memory may be strongly tied the initial learning format (Shelton & McNamara, 2004). In a series of experiments using route and survey texts and videos, Shelton and McNamara found that participants adhere to a principle reference vector (i.e., first path segment of a route, or north as up with survey) for scene recognition. Thus, spatial memory likely preserves orientation specificity based on a principle reference vector that is defined by certain description elements. Flexible inferencing, in contrast, may be strongly tied to the availability of a spatial mental model. Further insights into the nature of spatial memory can be obtained by detailing the time course by which people develop these models, the processes underlying their development, and the format of the resultant representation.

Recent work has demonstrated the relative difficulty of developing spatial mental models from route versus survey descriptions (Brunyé & Taylor, 2007; Lee & Tversky, 2005; Noordzij & Postma, 2005). With limited exposure (i.e., a single read) to route and survey descriptions, spatial mental models are more likely to develop from the latter; in contrast, with repeated exposure operationalized as three read cycles, spatial mental models develop with either description perspective (Brunyé & Taylor, 2007). However, even with this repeated exposure, reading times suggest greater difficulty processing route descriptions. This difficulty may be due to at least the following: first, route descriptions present spatial information embedded within a sequential framework that requires updating relative to a principle reference vector defined by the initial path segment (i.e., Shelton & McNamara, 2004); second, route descriptions may demand a high degree of complex (i.e., 3D) mental imagery as a reader imagines moving through the environment (i.e., Fincher-Kiefer, 2001); finally, landmark interrelationships must be inferred (rather than directly acquired) from route descriptions (i.e., Tversky, 1993).

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Developing spatial mental models

A fundamental question for discourse research is whether mental models are constructed during comprehension or later during application. Much recent work suggests that spatial information may only be tracked in the context of relevant cues such as reading goals, temporal shifts, and causal relatedness (e.g, de Vega, 1995; Jahn, 2004; Levine & Klin, 2001; Magliano, Miller, & Zwaan, 2001, 2005; Morrow, Greenspan, & Bower, 1987; Rapp & Taylor, 2004; Rich & Taylor, 2000; Zwaan et al., 1995; Zwaan et al., 1998). Thus, mental models containing comprehensive spatial information may only develop under very limited circumstances.

Spatial descriptions provide a special case for text comprehension models, in that they differ from narrative discourse with their focus on spatial relation information (e.g., landmark interrelationships) and omission of causality, intentionality, and explicit agent-based information. Recent work has demonstrated the utility of discourse models in explaining spatial and non-spatial expository text comprehension (i.e., Cote, Goldman, & Saul, 1998; Graesser & Bertus, 1998; Taylor & Tversky, 1992a). When reading spatial descriptions there is a primary implied goal: to understand an environment's elemental interrelationships. This is supported by work showing that spatial mental models develop without the influence of explicit goals or causal relatedness cues (e.g., Ferguson & Hegarty, 1994; Lee & Tversky, 2005; Taylor & Tversky, 1992a, 1992b).

An underlying assumption of the present work, therefore, is that spatial inferences may be formed spontaneously during spatial description reading as a consequence of at least two mechanisms. First, by making spatial information exceedingly salient, spatial descriptions implicitly establish the goal of tracking and drawing inferences about spatial relationships (i.e., Levine & Klin, 2001; Taylor, Naylor, & Chechile, 1999; van den Broek, Lorch, Linderholm, & Gustafson, 2001). Second, having few dimensions (i.e., spatial, temporal), the spatial descriptions prioritize the allocation of cognitive resources towards tracking spatial information (i.e., Estevez & Calvo, 2000; Linderholm & van den Broek, 2002; Morra, 2001). An accurate spatial mental model results from actively tracking and representing spatial relationships (Morrow, 1994; Rinck, Hanhel, Bower, & Glowalla, 1997). In our view, readers of spatial descriptions actively monitor spatial relation information, make certain inferences about relationships that are not explicit, and develop a spatial mental model. These models are abstractions that go beyond what is read, and they are perspective-*flexible* in that people use them to think about environments from different perspectives. The present work therefore adopts existing operational definitions of spatial mental models (i.e., Gyselinck, De Beni, Pazzaglia, Meneghetti, & Mondoloni, 2007; Pazzaglia, De Beni, Gyselinck, & Meneghetti, 2007; Taylor & Tversky, 1992a; Tversky, 1991, 1993). Note that these models are quite different from the notions of a cognitive map (i.e., Tolman, 1948) or a cognitive collage (i.e., Tversky, 1993). The first is a perspective-inflexible representation that preserves a map-like allocentric structure in memory, and the second is a multi-perspective but incomplete representation and a potential precursor to a spatial mental model.

We explore the development and use of these models to elucidate *when* (i.e., reading, application) and *how* (i.e., which working memory mechanisms) they develop, and *what* form they take in memory.

Working memory and selective interference

The present studies address these goals using a selective interference paradigm during either reading or memory application. We examine three working-memory subsystems: the visuospatial sketchpad, articulatory rehearsal loop, and the central executive (i.e., Baddeley, 1992, 2002; see also the episodic buffer, Baddeley, 2000, which is not examined here). Selective interference paradigms typically involve suppressing one of these working memory subsystems, with any observed memory deficits implicating involvement of that mechanism towards learning.

The visuospatial sketchpad appears to be involved in processing object-based visual features such as found in picture-based procedures, diagrams, and maps (e.g., Brunyé, Taylor, Rapp, & Spiro, 2006; Garden, Cornoldi, & Logie, 2001; Gyselinck, Cornoldi, Dubois, De Beni, & Ehrlich, 2002; Kruley, Sciama, & Glenberg, 1994; Logie, 1995), locations and movements in space (De Beni, Pazzaglia, Gyselinck, & Meneghetti, 2005), and spatial visualization and mental imagery (Farmer, Berman, & Fletcher, 1986; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). Investigating visuospatial involvement during spatial description reading allows us to assess the extent to which readers actively track spatial information during reading (i.e., Zwaan & Radvansky, 1998), and how this tracking may translate into spatial mental model development.

The articulatory component of working memory is generally involved in processing verbal information across the auditory (Baddeley, Lewis, & Vallar, 1984; De Beni et al., 2005; Longoni, Richardson, & Aiello, 1993), visual (Brunyé et al., 2006; Farmer et al., 1986; Goldman & Healy, 1985), and even tactile modalities (Millar, 1990). Using an articulatory secondary task during reading allows us to assess the verbal processes involved in developing spatial mental models, and the extent to which these processes (i.e., developing a propositional base; van Dijk & Kintsch, 1983) lay a foundation for spatial mental model development.

The central executive is relatively less well-understood, but is thought to involve supervisory control of working memory subsystems (Baddeley, 1996; Baddeley, Emslie, Kolodny, & Duncan, 1998; Duff, 2000). The central executive has been implicated in: coordinating performance between two separate tasks or information formats (e.g., Brunyé et al., 2006; Della Sala, Baddeley, Papagno, & Spinnler, 1995; Duff, 2000; Duff & Logie, 2001; Gyselinck et al., 2002), generating random sequences (e.g., Baddeley, 1996; Baddeley et al., 1998; Brunyé et al., 2006), inferencing and analogical reasoning (Morrison, 2004), attending to one and inhibiting disruption of another stimulus (e.g., Baddeley, 2002), and temporal tagging (Miyake & Shah, 1999; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Using central executive tasks during reading allows us to assess their involvement in sequential processing, and the allocation of resources between other subsystems. In turn, it can provide insights into the nature of spatial mental models.

Recent work has demonstrated minimal influence of working memory capacity towards situation model updating (Radvansky & Copeland, 2001), relatively greater involvement in the initial development of situation models (Radvansky & Copeland, 2006a, 2006b), and important roles for integrative processes and drawing inferences towards successful narrative discourse comprehension (Radvansky & Copeland, 2004a, 2004b). We extend this work by selectively and individually examining working memory subsystems, complementing this group's findings with general span measures. Specifically, composite span indicators that consider multiple subsystem span test scores may limit conclusions with regard to individual subsystem contributions during reading and retrieval. In line with this work, we propose that working memory will be primarily involved during the initial development of situation models during reading (i.e., Radvansky & Copeland, 2006a, 2006b), less involved in the direct retrieval of these models from long term memory (i.e., Pazzaglia et al., 2007; Radvansky & Copeland, 2006a, 2006b), and recruited when inference processes are demanded by the task (i.e., Radvansky & Copeland, 2004b). These hypotheses are in contrast to the notion that the automatic resonance of sentence- and discourse-level information can proceed without high working memory demands (e.g., Myers & O'Brien, 1998; O'Brien & Myers, 1999).

Experiment 1

The present experiment incorporates two widely-used suppression tasks (Brunyé et al., 2006; De Beni et al., 2005; Farmer et al., 1986; Gyselinck et al., 2002) during spatial description reading: a visuospatial finger-tapping task and an articulatory syllable string repetition task. Recent work using the secondary finger-tapping task has demonstrated that route descriptions, relative to non-spatial sequential texts, preferentially recruit visuospatial resources (De Beni et al., 2005; Pazzaglia et al., 2007); a verbal secondary task interfered with both description types, suggesting articulatory mechanisms while reading both spatial and non-spatial texts. However, the primary (listening) and secondary (oral syllable string repetition) tasks used in this previous work may have produced perceptual interference making it difficult to isolate any working memory interference. The present experiment extends this work to route and survey spatial descriptions, and uses secondary tasks designed to produce working-memory, and not perceptual, interference.

A series of hypotheses guide this experiment. First, a control group without secondary interference is expected to replicate earlier work demonstrating that participants develop spatial mental models from both survey and route descriptions and these mental models afford cross-perspective inferencing and map drawing. Second, visuospatial suppression is expected to interfere with mental model formation but not verbatim knowledge (i.e., knowledge gathered from information directly stated in the text), and interact with description perspective. We expect that visuospatial suppression will interfere to a greater extent with route than with survey texts. This hypothesis is based on work demonstrating increased difficulty in forming mental models from route relative to survey descriptions, due to increased demand for visuospatial resources (i.e., Brunyé & Taylor, 2007), and a strong reliance upon and updating relative to a principle reference vector (Shelton & McNamara, 2004). Articulatory suppression, however, is expected to interfere with both description types, particularly on measures of verbatim memory, in line with work demonstrating memory decrements following articulatory suppression during reading, across a variety of expository text types (e.g., Brunyé et al., 2006; Farmer et al., 1986; Goldman & Healy, 1985).

Methods

Participants

Forty-eight Tufts University undergraduates participated for partial course credit.

Materials

Spatial descriptions. Two environments, a convention center and town, were chosen from Taylor and Tversky's (1992a) materials (see Table 1). The survey descriptions for each environment were hierarchically organized, detailing global then local information, and described the environment from a 'bird's-eye' perspective using canonical (i.e., *north, south, east, west*) terms. The route description, in contrast, guided readers on a

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Table 1a
Survey and route perspective descriptions for the convention center environment

Survey description: Convention center	Route description: Convention center
Several companies that manufacture electronics have decided to get together for a convention to show their wares. A large convention center was chosen because its large rectangular floor plan can be easily changed to accommodate the needs of various conventions. Temporary wall dividers are used to separate the displays and to form a single entrance to each display. The displays have been grouped according to three categories–Visual Equipment, Personal Computers, and Audio Equipment. The rectangular center section of the building is divided into four displays for the visual equipment. In the northwest corner of the center section, with the entrance facing north, are the Televisions. Like many television displays, the sets are lined up along the walls, all tuned to the same station. In the northeast corner of the center section, with the entrance facing north, are the VCR's. In the southwest corner of the center section, with the entrance facing south, are the 35mm Cameras. In the southeast corner of the center section, with the entrance facing south, are the Movie Cameras. The Movie Cameras are set up to film people as they walk by the display. The remainder of the displays are along the outer, rectangular wall of the Convention Center. The east wall has only one display, the Personal Computers. This display is in the northeast corner and extends for about half of the east wall. There are software samples available for potential customers to test the various computers. Along the north wall are the two Audio Equipment displays–the Stereo Components and the CD Players. Along the north wall, directly west of the Personal Computers, are the Stereo Components. The Stereo Components display includes such items as receivers, turntables, speakers, and tape decks. Directly west of the Stereo Components are the CD Players. In addition to the displays, there are four permanent features of the Convention Center located along the west and south walls—the Cafeteria, the Restrooms, the Office, and the Bulletin Board. Just west of the CD Players, beginning in the northwest corner of the Convention Center and extending for about half of the west wall, is the Cafeteria. The Cafeteria is privately run by a family that leases the space on a permanent basis from the Convention Center. Directly south of the Cafeteria, on the west wall, are the Restrooms. Directly south of the Restrooms, extending from the southwest corner for about a third of the south wall, is the Office. East of the Office, covering about half of the south wall, is the Bulletin Board. The Bulletin Board is used in every convention for the business cards of the participating companies. East of the Bulletin Board, on the east side of the building near the southeast corner, is the entrance.	Several companies that manufacture electronics have decided to get together for a convention to show their wares. A large convention center was chosen because its large, rectangular floor plan can be easily changed to accommodate the needs of various conventions. Temporary wall dividers are used to separate the displays and to form a single entrance to each display. The displays have been grouped according to three categories–Visual Equipment, Personal Computers, and Audio Equipment. You go to the east side of the building near the southeast corner where you find the entrance. As you walk into the building, you see, on your left, a Bulletin Board. The Bulletin Board is used in every convention for the business cards of the participating companies. Continuing straight ahead from the entrance, where the Bulletin Board is on your left, you reach, on your right, the Movie Cameras. The Movie Cameras are set up to film people as they walk by the display. Walking past the Movie Cameras on your right, you see, again on your right, the 35mm Cameras. On your left, stretching into the corner of the building, is the Office. From the Office, you are forced to turn right and you see, to your immediate left, the Restrooms. You continue forward from the Restrooms until you see, on your left stretching into the corner of the building, the Cafeteria. The Cafeteria is privately run by a family that leases the space on a permanent basis from the Convention Center. From the Cafeteria, you walk forward, until you are forced to turn right and you see, to your immediate left, the CD Players. On your right are the Televisions. Like many television displays, the sets are lined up along the walls, all tuned to the same station. You walk past the Televisions, on your right, and continue forward until you see, again on your right, the VCR's. On your left are the Stereo Components. This display includes such items as receivers, turntables, speakers, and tape decks. From the Stereo Components you walk forward until you are forced to turn right and you see, to your immediate left, the Personal Computers. There are software samples available for potential customers to test the various computers. From the Personal Computers, you walk until you reach, on your left, the corridor leading to the entrance of the building.

linear mental tour through the environment, making the fewest possible turns while mentioning all landmarks along a continuous path, using egocentric terms (i.e., *on your right, in front of you*). The survey and route versions of each description were equated along several dimensions: similar text lengths, informationally equivalent (i.e., conveyed equivalent landmark interrelationship information), no indeterminate object locations, and equal coherence according to pilot judgments (Taylor & Tversky, 1992a).

Secondary tasks. Two secondary tasks were used: one visuospatial (finger tapping) and one articulatory (syllable string repetition). The visuospatial task involved repeatedly tapping four keys (2, 4, 6, 8) on a numeric keypad in a counter-clockwise rotation. The articulatory task involved repeating the sequence 'BA BE BI BO' aloud. Both tasks were done at a rate approximating 1 tap (spatial) or 1 syllable (verbal) per second.

Dependent measures. The present experiment incorporated two memory tasks: statement verification and map drawing. The statement verification task assessed description knowledge that could be directly (verbatim) and indirectly (inference and paraphrase) acquired from the text. Verbatim trials probed locative and non-locative knowl-

Table 1b
Survey and route perspective descriptions for the town environment

Survey description: Town	Route description: Town
One of the largest town fairs and pumpkin festivals in the United States is held each year in the town of Etna. Etna is a typical small New England town. The lay-out of the town has not changed much since it was founded in the 1700s. Etna and its surrounding areas are bordered by four major landmarks: the White Mountains, the White River, the River Highway, and Mountain Rd. The northern border is made up of the White Mountain Range. Running north-south along the western border of this region is the White River. The southern border is made up of the River Highway. Along the eastern border, connecting the River Highway to the mountains, is Mountain Rd. Most of Etna lies west of Mountain Rd. just north of its intersection with the River Highway. Etna is built around four streets that surround the Town Park. On the eastern edge of the park, there is a white Gazebo. The Gazebo is used to house the town band during afternoon concerts. Along the eastern edge of the Town Park runs Mountain Rd. The other three streets in Etna are each only a block long. Along the southern border of the park runs Maple St. Maple St. is lined with large maple trees. These maples, when they come alive with color in the fall are an attraction for many tourists. Across the street from the park, on separate sides, lie three of the town's main buildings–the Town Hall, the Store, and the School. Across the street from the east side of the park is the Town Hall. The Town Hall is the oldest structure in the town and one of the buildings around which the town was built. Across the street from the north side of the park is the Store. People often gather at the Store to find out the latest town news. Across the street from the west side of the park is the School. The little red, one-roomed schoolhouse is the original school built when the town was founded. At the northwest corner of River Highway and Mountain Rd. is the Gas Station. One of the mechanics from the Gas Station sits in front of the station office and waves to all the cars that drive past.	One of the largest town fairs and pumpkin festivals in the United States is held each year in the town of Etna. Etna is a typical small New England town. The lay-out of the town has not changed much since it was founded in the 1700s. To reach Etna, drive east along the River Highway to where the highway crosses the White River. Continuing on the River Highway, for another half mile past the river you come to, on your left, Mountain Rd. You have reached the town of Etna. As you turn left onto Mountain Rd. from the River Highway, you see, on your immediate left, the Gas Station. One of the mechanics from the Gas Station sits in front of the station office and waves to all the cars that drive past. Straight ahead, you can see the road disappearing into the distant White Mountains. You drive on Mountain Rd. a block past the Gas Station, and come to, on your left, Maple St. Turning left onto Maple St., you see that the street is lined with large maple trees. These maples, when they come alive with color in the fall, are an attraction for many tourists. After turning left onto Maple St. from Mountain Rd., you see, on your right, the Town Park—a central feature of Etna. You travel a block on Maple St. and are forced to make a right turn. On your left, about a half a block after you turn off of Maple St., is the School. The little red, one-roomed schoolhouse is the original school built when the town was founded. Continuing along this street for another half a block, you are again forced to make a right turn. You turn and drive a half a block where you see, on your left, the Store. People often gather at the Store to find out the latest town news. This road continues for another half a block where it dead-ends into Mountain Rd. After you make a right turn onto Mountain Rd., you drive about a half a block to where you see, on your left, the Town Hall. The Town Hall is the oldest structure in the town and one of the buildings around which the town was built. From your position with the Town Hall on your left, you see, on your right, a white Gazebo near the edge of the park. The Gazebo is used to house the town band during afternoon concerts. You return to where Mountain Rd dead-ends into the River Highway. You turn left from Mountain Rd. and leave the town of Etna by taking the River Highway.

edge. A total of eight verbatim locative statements and four verbatim non-locative statements were derived from route and survey descriptions for each environment. Inference trials probed locative information not directly conveyed by the text. For each environment a total of twelve inference statements took on route (6) and survey (6) perspectives. Note that across-perspective verbatim locative statements are always considered inference questions. Four paraphrase verification trials probed non-locative information not directly imparted by the text. Henceforth these trial types will be termed 'statement types'. There were 22 (78.5% of items) true and six (21.5% of items) false statements in the statement verification task. The map drawing task involved self-paced drawing of sketch maps on blank paper.

Procedures

Learning. Each participant learned both the town and convention center, in either a route or survey perspective in a counterbalanced manner (one from a route perspective and one from a survey perspective). That is, participants read a single description (e.g., town in survey perspective) three times in succession, and then advanced to memory testing; they then read a second description (e.g., convention center in route perspective) three times in succession, and then advanced to memory testing. Descriptions, presented using SuperLab™ software for the Macintosh™ appeared in 14-point bold Times New Roman font, one sentence at a time on the computer screen. Presentation rates were established by examining reading rates in a pilot study, during

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which eight participants learned route and survey versions of the descriptions in a self-paced manner. Based on these data, presentation rates were set at the average reading time for each sentence plus 2.5 *SD*. Each description was presented three times in succession.

Secondary tasks. Participants were divided into three secondary task groups: control (no secondary task), visuospatial (tapping with non-dominant hand), and articulatory (syllable repetition). Participants practiced their assigned task to criterion (perfect performance for three consecutive strings). Experimenters verbally encouraged tapping and repetition rates of approximately one response (tap, syllable) per second.

Dependent measures. Participants completed the memory after each of the two learning sessions, in a counterbalanced manner, as quickly as possible without compromising accuracy. Participants responded to statement verification trials by pressing keys labeled as *true* (C) or *false* (M) with their dominant hand. Accuracy and response time were recorded. The map drawing task was limited to 10-min.

Results

Scoring

Statement verification. Accuracy was averaged for each statement type within each description type (route, survey). Response times were averaged for correct trials only, for each statement type. To test for response bias we conducted a total of 96 McNemar χ^2 tests for dichotomous (true/false) variables, one for each participant's statement verification data, none of which revealed observed response proportions biased in the "true" direction ($\chi^2_{\max} = 2.21$, all ps > .05).

Map drawing. Map scoring evaluated landmark recall, relative landmark locations, and quadrant accuracy. Landmark recall is the proportion of landmark names correctly recalled relative to the total number presented (12). Relative landmark location accuracy assesses correspondence with 26 landmark-to-landmark comparisons derived from the survey and route descriptions (e.g., Is the store north of the town hall?). Quadrant accuracy provides an assessment of global configuration, computed by dividing each sketch map into quadrants along predetermined north and south axes, and summing the number of landmarks drawn within each quadrant. This (denominator) was compared with the number of landmarks correctly drawn within the quadrant (numerator).

Analysis

For all analyses, we confirmed that there was no main effect of or interactions with learning order (survey or route first or second; all ps > .10, $F_{\max} = 2.21$).

Statement verification. Three 3(secondary task: control, visuospatial, articulatory) × 2(study perspective: route, survey) × 2(statement type: varied for each ANOVA) mixed models ANOVAs were performed on both accuracy and response time data from verbatim locative, verbatim and paraphrased non-locative, and inference statements. Note that study and testing combinations that cross perspectives require inferencing and were treated as such. To ensure that are response time results were not driven (or masked) by a positively-skewed distribution, all analyses (across all experiments) were also completed using log(10) transformed data; these analyses did not yield different results than the pre-transformed data, and thus are not reported here.

Map drawing. Three 3(secondary task: control, visuospatial, articulatory) × 2(study perspective: route, survey) mixed models ANOVAs were performed on data from the three map scoring procedures.

Planned comparisons. Across all analyses, planned comparisons were performed using t-tests with Bonferroni corrections for multiple comparisons.

Statement verification results: Accuracy

Locative verbatim items: Within- and across-perspective. As depicted in Fig. 1a, there was a main effect of secondary task, $F(2,45) = 19.82$, $p < .01$, $MSE = .01$. Planned comparisons revealed higher accuracy in the control group relative to both the visuospatial, $t(30) = 7.80$, $p < .01$, and the articulatory, $t(30) = 8.59$, $p < .01$, groups. In line with previous findings, an effect of statement type revealed highest accuracy within- rather than across-perspectives, $F(1,45) = 47.45$, $MSE = .02$, $p < .01$; the latter require inferencing. Finally, there was a secondary task by statement type interaction, $F(2,45) = 8.32$, $MSE = .02$, $p < .01$. Supporting our hypotheses, planned comparisons revealed that performance differences between the visuospatial and control groups showed up only when an inference was required: during across-perspective, $t(30) = 6.48$, $p < .01$, and not within-perspective, $t(30) = 1.06$, $p > .05$, trials. There were no other effects for these statement types (Fs < 1).

Non-locative verbatim and paraphrased statements. There was a main effect of secondary task for these statement types, $F(2,45) = 17.38$, $p < .01$, $MSE = .01$. Supporting the notion that articulatory secondary tasks interfere with description reading in a broad-based manner, planned comparisons revealed higher accuracy in the control group ($M = .97$, $SE = .02$) relative to the articulatory ($M = .87$, $SE = .02$), $t(30) = 5.34$, $p < .01$, but not the visuospatial ($M = .95$, $SE = .02$), $t(30) = 1.12$, $p > .05$, group. There were no other effects for these statement types (Fs <1).

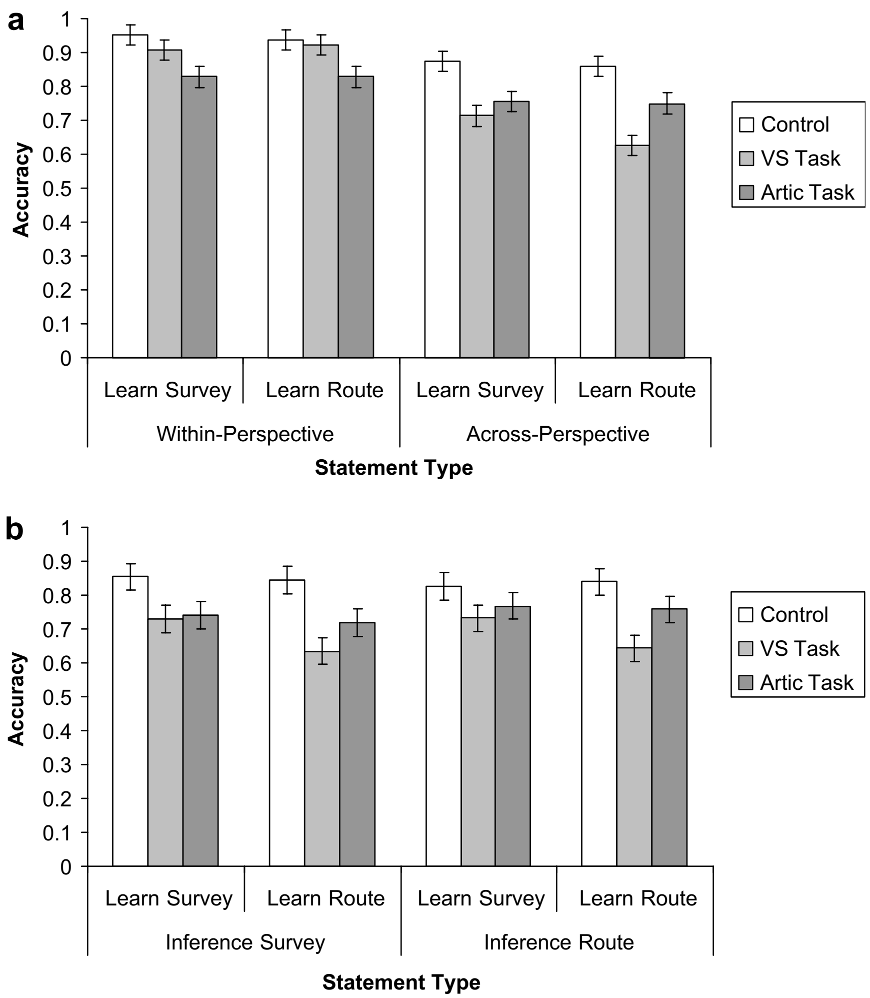

Fig. 1. (a and b) Experiment 1 mean accuracy and standard error on the statement verification task for (a) locative verbatim items, within and across perspective, and following survey and route learning, and (b) locative inference items, following survey and route learning. Results are displayed by secondary task group.

Locative inference statements: Survey and route. There was a main effect of secondary task for these statement types, $F(2,45) = 36.79$, $p < .01$, $MSE = .01$. Planned comparisons revealed higher accuracy in the control group ($M = .86$, $SE = .02$) relative to the articulatory ($M = .74$, $SE = .02$), $t(30) = 6.26$, $p < .01$, and visuospatial ($M = .69$, $SE = .01$), $t(30) = 7.55$, $p < .01$, groups (see Fig. 1b). Further, secondary task interacted with description perspective, $F(2,45) = 3.33$, $p < .05$, $MSE = .01$. Whereas both secondary tasks reduced inferencing accuracy following survey description learning, the visuospatial task had a relatively pronounced influence following route description learning. There were no other effects for these statement types (Fs < 1).

Statement verification results: Response times

Locative verbatim items: Within- and across-perspective. There was a main effect of secondary task for these statement types, $F(2,45) = 4.83$, $p < .05$, $MSE = 2.65$. Planned comparisons revealed faster response times in the control group ($M = 5.99$, $SE = .21$) relative to the visuospatial ($M = 6.84$, $SE = .21$), $t(30) = 3.41$, $p < .01$, but not the articulatory ($M = 6.64$, $SE = .21$), $t(30) = 1.89$, $p < .025$, group. Demonstrating the added difficulty in perspective-switching during inference generation, an effect of statement type revealed faster response times within- ($M = 4.83$, $SE = .11$) compared to across-perspectives ($M = 8.14$, $SE = .17$), $F(1,45) = 380.85$, $MSE = 1.39$, $p < .01$. Finally, there was a secondary task by statement type interaction,

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$F(2,45) = 6.23$, $MSE = 1.39$, $p < .01$. Response time differences between visuospatial and control groups existed only for across-, $t(30) = 4.62$, $p < .01$, and not within-perspective, $t(30) = .604$, $p > .05$, trials. There were no other effects for these statement types (Fs < 1).

Verbatim and paraphrased non-locative statements. There were no significant main effects or interactions for these statement types (all ps $> .05$).

Locative inference survey and route statements. There was a main effect of secondary task for these statement types, $F(2,45) = 5.89$, $p < .01$, $MSE = 6.15$. Complementing the accuracy results, planned comparisons revealed faster response times in the control group relative to the visuospatial, $t(30) = 3.47$, $p < .01$, but not the articulatory, $t(30) = 1.50$, $p > .025$, group (see Fig. 2). There were no other effects for these statement types (Fs <1).

Map drawing

Landmark recall. There was a main effect of secondary task for this measure, $F(2,45) = 7.59$, $p < .01$, $MSE = .02$. Supporting our prediction that articulatory secondary tasking interferes with declarative memory formation, the articulatory group ($M = .77$, $SE = .02$), $t(30) = 3.77$, $p < .01$, but not visuospatial group ($M = .87$, $SE = .02$), $t(30) = .76$, $p > .05$, showed reduced landmark recall relative to the control group ($M = .90$, $SE = .02$). There were no other effects for this measure.

Relative landmark location. There was a main effect of secondary task for this measure, $F(2, 45) = 30.37$, $p < .01$, $MSE = .01$. Supporting our prediction that visuospatial secondary tasking interferes with local configural knowledge development, the visuospatial, $t(30) = 7.36$, $p < .01$, but not articulatory group, $t(30) = 1.91$, $p > .05$, showed reduced relative landmark location accuracy relative to the control group (see Fig. 3). There were no other effects for this measure.

Quadrant accuracy. There was a main effect of secondary task for this measure, $F(2,45) = 3.18$, $p < .10$, $MSE = .01$. Supporting our prediction that visuospatial secondary tasking interferes with global configural knowledge development, the visuospatial ($M = .90$, $SE = .02$), $t(30) = 2.75$, $p < .01$, but not articulatory group ($M = .93$, $SE = .02$), $t(30) = 1.34$, $p > .05$, showed reduced quadrant accuracy relative to the control group ($M = .97$, $SE = .02$). There were no other effects for this measure.

Discussion

In this experiment, three participant groups learned route and survey spatial descriptions with either no secondary task, a visuospatial secondary task, or an articulatory secondary task. The control group (i.e., no secondary task) replicated the main results of Taylor and Tversky (1992a); specifically, while these participants were faster and more accurate at verifying verbatim locative relative to inference statements, they could solve spatial inferences presented in both perspectives roughly equivalently, regardless of learning perspective. This could be seen in both statement verification and map drawing. Participants developed spatial mental models from both perspective descriptions and used them successfully at test.

The visuospatial secondary task interfered with spatial mental model development, evidenced by lower performance on several memory measures (inferencing,

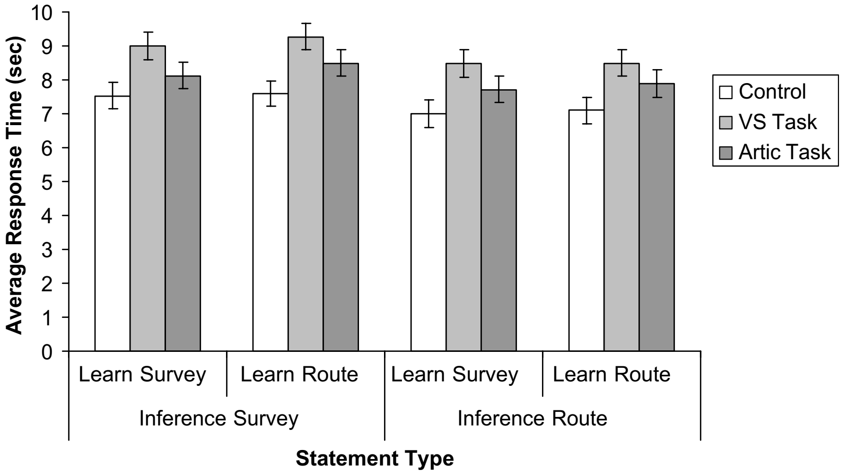

Fig. 2. Experiment 1 mean response time and standard error on the statement verification task for locative inference items, following survey and route learning, displayed by secondary task group.

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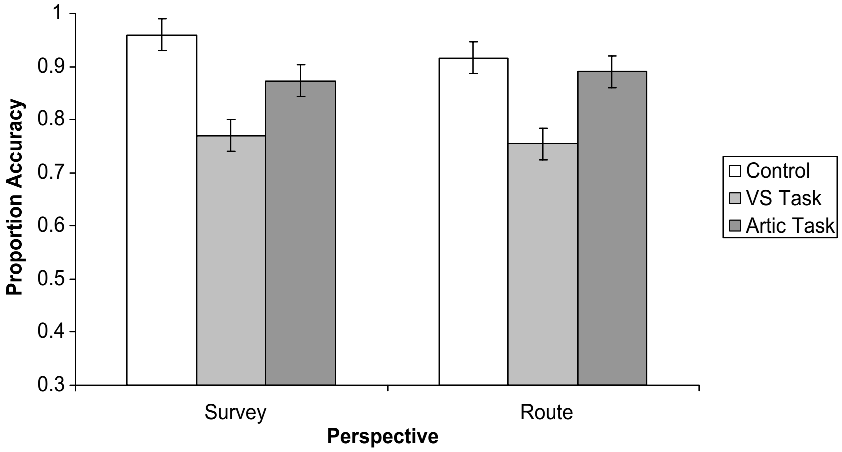

Fig. 3. Experiment 1 mean accuracy and standard error on the relative landmark location scoring procedure for the map drawing task, displayed by secondary task group.

relative map landmark location, and map quadrant accuracy) relative to the control group. Further, the visuospatial task interfered more with inferencing accuracy following route, relative to survey, learning. The latter effect supports the notion that with route descriptions, additional visuospatial resources may be involved in monitoring and updating information relative to a principle reference vector (i.e., Shelton & McNamara, 2004), and forming rich mental imagery (Brunyé & Taylor, 2007; Farmer et al., 1986; Miyake et al., 2001). In contrast, visuospatial suppression did not interfere with nonlocative (verbatim or paraphrased) or verbatim locative verification following route or survey learning. Map drawing revealed similar results, with visuospatial interference showing up in both relative landmark location (local spatial knowledge) and quadrant accuracy (global spatial knowledge) results, but not in landmark recall (declarative knowledge) results.

Articulatory suppression produced decrements across verification tasks requiring the application of declarative memories and spatial mental models. These results speak to the importance of articulatory mechanisms during spatial description reading, regardless of perspective, allowing readers to gather the verbal foundation for developing both declarative memories *and* spatial mental models. This finding is in line with the notion that readers progress from a representation of the text itself (i.e., the surface form), to a text-base or propositional form, to a mental model of the described environment (i.e., van Dijk & Kintsch, 1983); interfering with articulatory processes during reading reduces the ability to extract the elements necessary for forming propositions. These findings are also similar to those found in other selective interference work (Canas et al., 2003; Pazzaglia et al., 2007). In contrast to our hypothesis, the effects of articulatory suppression did not show up in response times to declarative memory measures. The data suggest a trend in this direction, but did not reach significance.

Across all dependent measures and scoring procedures, interactions with description perspective, verification type and scoring procedure allow us to dissociate the difficulty and selectivity of our two secondary tasks. To the extent that a given secondary task is relatively demanding overall, interactive effects upon memory performance as a function of description perspective, and a consistent comparison *only* to control group performance, should preclude difficulty—rather than selectivity-based interpretations. Indeed our findings are congruent with recent work using both the same *and* different tasks; for instance, we provide converging evidence that our articulatory task interferes with verbal resources in general—the result of which is broad-based when the learning materials are verbal in nature (e.g., descriptions; De Beni et al., 2005; Pazzaglia et al., 2007), but not when they are solely spatial in nature (e.g., diagrams and maps; Brunyé et al., 2006; Canas et al., 2003).

The present results also expand the findings of De Beni and colleagues (2005), demonstrating that both articulatory and visuospatial processes are important working memory processes for route and survey spatial discourse comprehension and memory. They also support the notion that route descriptions present additional cognitive demands relative to survey descriptions (Brunyé & Taylor, 2007; Lee & Tversky, 2005; Shelton & McNamara, 2004) as evidenced by greater visuospatial interference. Our results demonstrate that spatial information is in fact tracked when people read spatial descriptions, likely in an effort to form inferences and develop mental models of the environment, especially when other indexes are limited, as suggested by the extant literature (i.e., de Vega, 1995; Levine & Klin, 2001; McKoon & Ratcliff, 1992; Taylor et al., 1999).

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Experiment 2

Our first experiment demonstrated the unique contributions of visuospatial and articulatory mechanisms; our second experiment investigates central executive functions during spatial description reading. Two central executive functions are of interest—resource coordination, and spatial-sequential processing. One secondary task was designed to interfere with the *coordination* of visuospatial and articulatory resources through random generation. The other was designed to interfere with *temporal indexing* through sequential updating (i.e., a two-back working memory task).

Random generation appears to require central executive involvement towards the switching of retrieval plans and repetition inhibition in an effort to avoid falling into perceptible patterns (i.e., Baddeley et al., 1998; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Miyake et al., 2001). These same resources appear to be necessary for the switching between and eventual integration of visuospatial and articulatory representations within working memory (Brunyé et al., 2006). Based on this analysis and Experiment 1 results we expect that route descriptions in particular will demand central resources for coordinating processes involved in representing the language itself and those involved in visuospatial thinking and mental imagery. Thus, random generation should interfere with both description perspectives due to their demand for spatial and verbal resources to develop spatial mental models, but should do so to a greater extent with route descriptions.

Auditory sequence monitoring requires continuous updating of sequential representations within working memory, another proposed central executive function (Brunyé et al., 2006; Miyake & Shah, 1999; Rabinowitz, Craik, & Ackerman, 1982). Based on this requirement and work illustrating the importance of monitoring and updating positions relative to a principle reference vector (Shelton & McNamara, 2004), we hypothesize that route, in contrast to survey, descriptions would demand more online sequence indexing during reading. While reading itself is a serial process, the added demand of monitoring and updating relative to an unfolding spatial-sequential framework leads to our prediction that route descriptions would recruit additional sequence indexing resources, beyond those needed for reading alone. This hypothesis is based on the assumption that readers spontaneously track sequential information in an effort to establish mental models (i.e., Radvansky, Zwaan, Federico, & Franklin, 1998; Rapp & Taylor, 2004), and that route descriptions in particular demand constant updating of egocentric orientations relative to a principle reference vector (Brunyé & Taylor, 2007; Shelton & McNamara, 2004). In summary, based on analysis of central executive processes, we hypothesize that both central executive directed secondary tasks, one requiring random generation and the other requiring sequence updating, would detrimentally impact route, compared to survey, description reading.

Methods

Participants

Thirty-two Tufts University undergraduates participated for partial course credit, randomly divided into two groups: 16 for the random generation task, and 16 for the sequence monitoring task. Because multiple experiments in our labs have replicated the stability of the control group means across participant samples, time frames, and universities, data from Experiment 1 control participants comprise the control groups in Experiments 2–4. See Tables 2–4 for several studies that have used identical stimuli and dependent measures; these data demonstrate the reliability of means across dependent measures, experiments, and institutions.

Materials

Materials were identical to those used in Experiment 1 with the exception of the two secondary tasks.

Secondary tasks. Two secondary tasks were used, one involving self-paced random generation (finger tapping) and one involving experimenter-paced sequence monitoring (auditory). The random generation task was similar to Experiment 1s finger tapping task, but involved random, rather than sequential counter-clockwise, production of finger taps. We chose a random finger tapping, as opposed to syllable-string production, as previous work has demonstrated similar central demands of both tasks (Brunyé et al., 2006), and finger tapping is relatively amenable to multiple-participant experimental sessions. The sequence monitoring task was adapted from Rabinowitz and colleagues (1982). Participants listened to a sequence of monotonic beeps occurring in their left and right ears, monitoring for a target sequence of three consecutive beeps in their left ear. Beeps were approximately 500 ms in duration, with an ISI of 1000 ms. The full recording was 650-beeps in length, with the following constraints (Rabinowitz et al., 1982): at least one and no greater than five beeps could occur between target sequences and no more than two right ear beeps could occur in sequence.

Procedures

Procedures were identical to those used in Experiment 1 with the exception of the two secondary tasks.

Secondary tasks. Participants were divided into two secondary task groups: random tapping and sequence monitoring. Participants received instructions for their assigned task and practiced to criterion. The criterion for the random generation task was 60 s of tapping at

Table 2
Control group means reflecting accuracy on the statement verification tasks across experiments and institutions

Authors (year)	Data collection site	Survey learning		Route learning	
		M	*SE*	*M*	*SE*
Measure: Statement type					
Present control data	Tufts University				
Accuracy: Locative					
Within-perspective		.95	.025	.94	.027
Across-perspective		.88	.032	.86	.032
Accuracy: Non-locative					
Verbatim		.98	.021	.97	.021
Paraphrased		.96	.025	.95	.028
Accuracy: Locative inference					
Inference survey		.85	.032	.84	.032
Inference route		.83	.031	.84	.030
Brunyé and Taylor (2007)	Tufts University				
Accuracy: Locative					
Within-perspective		.96	.021	.95	.042
Across-perspective		.84	.026	.83	.031
Accuracy: Non-locative					
Verbatim		.98	.017	.98	.015
Paraphrased		.97	.019	.96	.019
Accuracy: Locative inference					
Inference survey		.83	.043	.83	.047
Inference route		.82	.044	.89	.030
Brunyé (2007) (*Experiment 7*)	Dartmouth College				
Accuracy: Locative					
Within-perspective		.97	.014	.95	.018
Across-perspective		.87	.030	.85	.037
Accuracy: Non-locative					
Verbatim		.97	.015	.97	.019
Paraphrased		.96	.016	.95	.018
Accuracy: Locative inference					
Inference survey		.84	.041	.83	.039
Inference route		.85	.033	.89	.028
Taylor and Tversky (1992a, 1992b)	Stanford University				
Experiment 1					
Accuracy: Locative					
Within-perspective		.95	.031	.97	.029
Across-perspective		.82	.030	.84	.011
Accuracy: Non-locative					
Verbatim		.97	.013	.97	.012
Paraphrased		.96	.010	.95	.011
Accuracy: Locative inference					
Inference survey		.89	.025	.88	.029
Inference route		.89	.021	.87	.024
Experiment 2					
Accuracy: Locative					
Within-perspective		.95	.042	.94	.027
Across-perspective		.75	.045	.83	.020

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Table 2 (*continued*)

Authors (year)	Data collection site	Survey learning		Route learning	
		M	*SE*	*M*	*SE*
Accuracy: Non-locative					
Verbatim		.97	.019	.95	.017
Paraphrased		.97	.010	.93	.021
Accuracy: Locative inference					
Inference survey		.86	.038	.81	.030
Inference route		.84	.027	.79	.039
Experiment 3					
Accuracy: Locative					
Within-perspective		.95	N/A	.96	N/A
Across-perspective		.82	N/A	.88	N/A
Accuracy: Non-locative					
Verbatim		.98	N/A	.98	N/A
Paraphrased		.96	N/A	.98	N/A
Accuracy: Locative inference					
Inference survey		.90	N/A	.88	N/A
Inference route		.89	N/A	.86	N/A

N/A, not available for retrieval.

an approximate 1 tap per second rate while inhibiting repetition or pattern-seeking. The experimenter verbally encouraged random tapping when participants fell into obvious patterns. The criterion for the sequence monitoring task was identifying three targets within a 27 beep practice session; to make sure participants were monitoring the task, they had to make tick marks on a sheet of paper upon identification of each target sequence.

Results

Analysis

Analyses were done in an identical manner to those of Experiment 1, substituting random generation and sequence monitoring secondary tasks for visuospatial and articulatory suppression. For all analyses, we confirmed that there was no main effect of or interactions with learning order (survey or route first or second), (all ps $> .10$, $F_{\max} = 1.69$).

Statement verification: Accuracy

A total of 64 McNemar χ^2 tests for response bias did not reveal response proportions biased in the "true" direction ($\chi^2_{\max} = 2.71$, all ps $> .05$).

Locative verbatim items: Within- and across-perspective. There was a main effect of secondary task for these statement types, $F(2,45) = 10.01$, $p < .01$, $MSE = .02$. Planned comparisons revealed that both secondary tasks interfered with learning, with higher accuracy in the control group ($M = .91$, $SE = .02$) relative to both random generation ($M = .82$, $SE = .02$), $t(30) = 4$, $p < .01$, and sequence monitoring ($M = .83$, $SE = .02$), $t(30) = 3.478$, $p < .01$, groups. An effect of statement type, $F(1,45) = 58.85$, $p < .01$, $MSE = .02$, revealed higher accuracy within- ($M = .92$, $SE = .01$) compared to across-perspectives ($M = .88$, $SE = .01$). Finally a secondary task by statement type interaction, $F(2,45) = 5.51$, $p < .01$, $MSE = .02$, revealed that secondary task performance differences were most pronounced for across-perspective study and test trials. That is, as predicted and in line with the extant literature, central executive interference occurred primarily when statement verification required inferencing. There were no other effects for these statement types (Fs <1).

Verbatim and paraphrased non-locative statements. There were no significant main effects or interactions for these statement types (all ps $> .05$).

Locative inference survey and route statements. There was a main effect of secondary task for these statement types, $F(2,45) = 20.8$, $p < .01$, $MSE = .01$. Planned comparisons revealed higher accuracy in the control group relative to the random generation, $t(30) = 5.94$, $p < .01$, and sequence monitoring, $t(30) = 4.520$, $p < .01$, groups (see Fig. 4). Further, secondary task interacted with study perspective, $F(2,45) = 4.72$, $p < .05$, $MSE = .01$. Follow-up contrasts using the Bonferroni correction revealed:

Learn survey, inference survey and route. Supporting our predictions, random generation, $t(30) = 2.88$, $p < .01$ and $t(30) = 2.49$, $p < .025$, reduced performance

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Table 3
Control group means reflecting response times (sec) on the statement verification tasks across experiments and institutions

Authors (year)	Data collection site	Survey learning		Route learning	
		M	*SE*	*M*	*SE*
Measure: Statement type					
Present control data	Tufts University				
Accuracy: Locative					
Within-perspective		4.52	.273	4.64	.382
Across-perspective		7.18	.538	7.59	.428
Accuracy: Non-locative					
Verbatim		4.45	.605	4.37	.284
Paraphrased		4.08	.339	4.59	.281
Accuracy: Locative inference					
Inference survey		7.53	.360	7.61	.428
Inference route		7.01	.543	7.09	.667
Brunyé and Taylor (2007)	Tufts University				
Accuracy: Locative					
Within-perspective		4.63	.303	4.58	.292
Across-perspective		7.11	.437	7.98	.342
Accuracy: Non-locative					
Verbatim		4.37	.456	4.46	.262
Paraphrased		4.01	.283	4.27	.304
Accuracy: Locative inference					
Inference survey		7.43	.598	7.40	.607
Inference route		6.96	.575	6.99	.508
Brunyé (2007) (*Experiment 7*)	Dartmouth College				
Accuracy: Locative					
Within-perspective		4.86	.223	5.13	.262
Across-perspective		7.39	.471	7.72	.530
Accuracy: Non-locative					
Verbatim		4.06	.307	4.69	.333
Paraphrased		4.38	.299	4.32	.341
Accuracy: Locative inference					
Inference survey		7.69	.309	7.12	.338
Inference route		7.42	.306	6.88	.265
Taylor and Tversky (1992a, 1992b)	Stanford University				
Experiment 1					
Accuracy: Locative					
Within-perspective		5.09	.296	5.22	.432
Across-perspective		7.63	.489	7.21	.362
Accuracy: Non-locative					
Verbatim		4.29	.328	3.76	.205
Paraphrased		4.63	.270	4.01	.208
Accuracy: Locative inference					
Inference survey		7.85	.284	7.28	.452
Inference route		8.06	.430	7.21	.511
Experiment 2					
Accuracy: Locative					
Within-perspective		4.74	.324	5.70	.428
Across-perspective		6.92	.394	6.62	.403

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Table 3 (*continued*)

Authors (year)	Data collection site	Survey learning		Route learning	
		M	*SE*	*M*	*SE*
Accuracy: Non-locative					
Verbatim		3.81	.419	3.96	.368
Paraphrased		3.75	.364	4.10	.253
Accuracy: Locative inference					
Inference survey		6.91	.462	6.95	.418
Inference route		7.83	.318	7.02	.486
Experiment 3					
Accuracy: Locative					
Within-perspective		5.12	N/A	5.04	N/A
Across-perspective		6.84	N/A	6.84	N/A
Accuracy: Non-locative					
Verbatim		3.77	N/A	3.72	N/A
Paraphrased		4.51	N/A	4.55	N/A
Accuracy: Locative inference					
Inference survey		7.05	N/A	6.82	N/A
Inference route		8.23	N/A	7.38	N/A

N/A, not available for retrieval.

Table 4
Control group means reflecting performance on the three map scoring procedures, across institutions

Authors (year)	Data collection site	Survey learning		Route learning	
		M	*SE*	*M*	*SE*
Scoring procedure					
Present control data	Tufts University				
Landmark recall		.91	.029	.89	.032
Relative landmark locations		.96	.020	.92	.030
Quadrant accuracy		.97	.023	.96	.018
Brunyé and Taylor (2007)	Tufts University				
Landmark recall		.90	.144	.91	.103
Relative landmark locations		.95	.078	.95	.081
Quadrant accuracy		.96	.051	.95	.101
Brunyé (2007) (*Experiment 7*)	Dartmouth College				
Landmark recall		.87	.041	.85	.039
Relative landmark locations		.95	.021	.91	.023
Quadrant accuracy		.96	.028	.94	.026

on both survey and route inferences (respectively). Sequence monitoring, however, did not for either perspective inferences ($ps > .05$).

Learn route, inference survey and route. For both survey and route inferences, sequence monitoring, $t(30) = 3.36$, $p < .01$ and $t(30) = 4.26$, $p < .01$, respectively, reduced performance. Random generation, $t(30) = 2.25$, $p < .025$ for survey inferences and $t(30) = 3.68$, $p < .025$ for route inferences, did as well.

Statement verification: Response times

Overall, response times from the statement verification task did not reveal any effect of secondary task.

Locative verbatim items: Within- and across-perspective. A main effect of study perspective revealed faster response times following survey ($M = 5.99$, $SE = .28$), relative to route ($M = 6.48$, $SE = .32$), study, $F(1,45) = 5.82$, $p < .05$, $MSE = 2.03$. An effect of statement type, $F(1,45) = 258.36$, $p < .01$, $MSE = 1.64$, revealed faster response times within- ($M = 4.75$, $SE = .16$) compared to across-perspectives ($M = 7.72$, $SE = .26$). There were no other effects for these statement types ($Fs < 1$).

Verbatim and paraphrased non-locative statements. There were no significant main effects or interactions for these statement types (all $ps > .05$).

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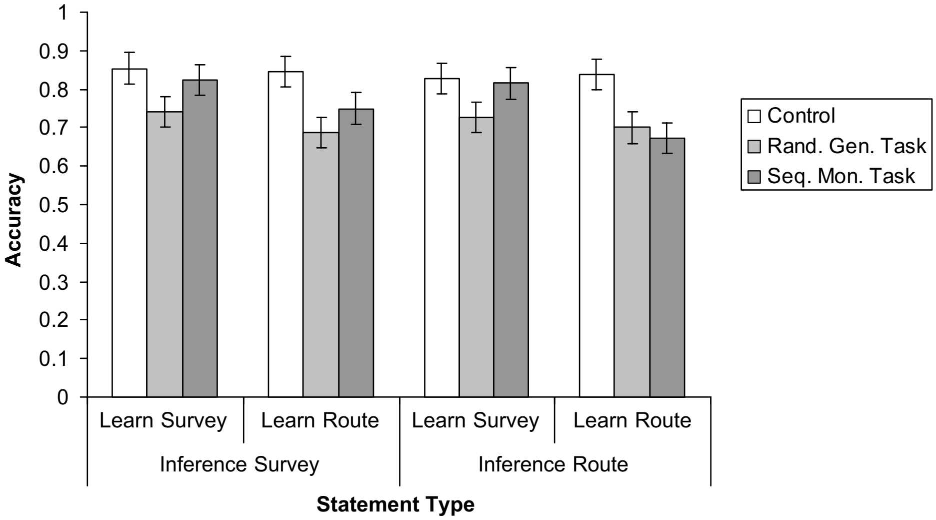

Fig. 4. Experiment 2 mean accuracy and standard error on the statement verification task for locative inference items, following survey and route learning, displayed by secondary task group.

Locative inference survey and route statements. There were no significant main effects or interactions for these statement types (all $ps > .05$).

Map drawing

Landmark recall. There were no significant main effects or interactions for this measure (all $ps > .05$).

Relative landmark location. There was a main effect of secondary task for this measure, $F(2,45) = 4.81$, $p < .05$, $MSE = .01$. Relative to the control group, both random generation, $t(30) = 2.44$, $p < .025$, and sequence monitoring, $t(30) = 2.94$, $p < .01$, reduced relative landmark location accuracy (see Fig. 5). Note that in line with our predictions sequence monitoring suppression appears primarily following route perspective learning—this interaction did not reach significance, however ($p < .10$). There were no other effects for this measure.

Quadrant accuracy. There was a main effect of secondary task for this measure, $F(2,45) = 3.49, p < .05, MSE = .01$. Relative to the control group ($M = .97$, $SE = .02$), both sequence monitoring ($M = .90$, $SE = .02$), $t(30) = 2.486$, $p < .025$, and random generation ($M = .91$, $SE = .02$), $t(30) = 2.45$, $p < .025$, reduced quadrant location accuracy. There were no other effects for this measure.

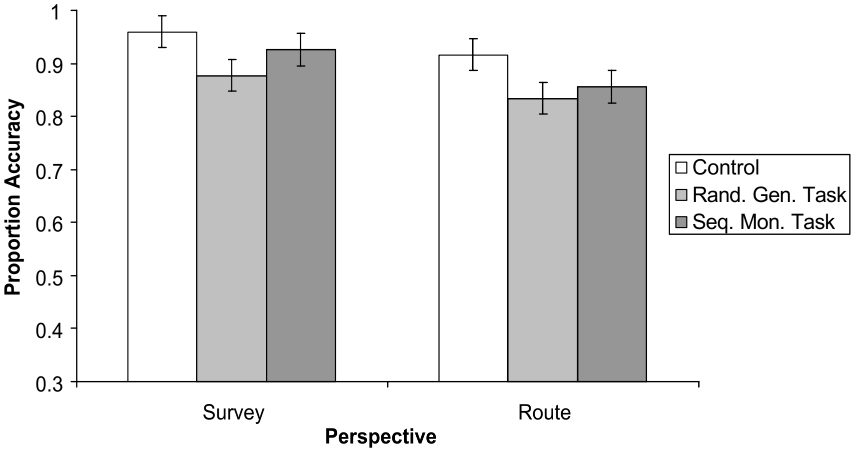

Fig. 5. Experiment 2 mean accuracy and standard error on the relative landmark location scoring procedure for the map drawing task, displayed by secondary task group.

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Discussion

In this experiment, we predicted that both central executive tasks, random generation and sequence monitoring, would interfere with route and survey learning; we also predicted that these effects would be most pronounced with route learning. Overall, the present results were generally congruent with hypothesized central executive functions as applied to spatial description reading, with some exceptions.

Interference from random generation was selective to mental model measures, and not measures of declarative memory. This effect was apparent for both description perspectives. Random generation interfered with survey and route inferencing accuracy; response time data mirrored this pattern but did not reach significance. Map drawing data also revealed marginally lower relative landmark location and quadrant accuracy for the random generation, relative to the control, group. Taken together, these results suggest that random generation interferes with spatial mental model formation. Given past work (Baddeley et al., 1998; Brunyé et al., 2006) we believe that random generation draws directly from central executive resources involved in the supervisory coordination of visuospatial (e.g., mental imagery) and articulatory (e.g., reading) systems. Further, the degree of central involvement appears to be similar for both route and survey descriptions, in contrast to our prediction that route descriptions would demand additional resources relative to survey descriptions.

Sequence monitoring during learning produced performance decrements that appear specific to forming spatial mental models from route, but not survey, descriptions. This was evidenced by reduced performance on both survey and route inferencing following route learning. In contrast, sequence monitoring did not appear to interfere with forming spatial mental models from survey descriptions, nor did sequence monitoring interfere with acquisition of declarative information. These results support the notion that readers of route descriptions monitor unfolding sequential information during route description reading; this monitoring process appears to aid in spatial mental model development, and may be initially tied to a principle reference vector (Shelton & McNamara, 2004). In further support of this finding, following route learning with sequential suppression, acquired memories were biased away from the egocentric perspective towards a relatively allocentric model, or cognitive map (i.e., Tolman, 1948; Kitchin, 1994). Specifically, these participants showed signs of perspective-specificity, but not congruent with the route format. It is likely that given the suppression of sequence processing, participants actively formed allocentric models to compensate for impoverished sequencing resources.

Although relatively less work has addressed central executive targeted secondary tasks, results from these two tasks targeting central executive processes support earlier findings in our own and others' labs (Baddeley et al., 1998; Brunyé, 2007; Della Sala et al., 1995; Duff, 2000; Duff & Logie, 2001; Miyake & Shah, 1999; Miyake et al., 2000). Random generation tasks appear to occupy resources used to actively select and integrate verbal and visuospatial information during learning, whereas the present two-back working memory task appears to interfere with sequence monitoring resources. These two central processes appear to be critical towards the development of spatial mental models during description reading.

Experiment 3

Our final experiments examine the effects of four secondary tasks after learning spatial descriptions, during application to statement verification and map drawing. A fundamental question in language research is whether readers develop mental models during reading, or if these models come together only as needed. Experiment 1 suggests that readers either form mental models during spatial description reading, or they gather the necessary information for later consolidation into mental models, perhaps during testing. The event indexing model (Zwaan et al., 1995; Zwaan & Radvansky, 1998) predicts mental model construction and updating during reading, ultimately resulting in coherent final memory representations. The resulting mental models code events both described within and inferred from the text. This assumption is supported by work demonstrating difficulty integrating incoming information into an evolving mental model when that information does not correspond well with a model's current state (e.g., Zwaan et al., 1995, 1998), or fit with a reader's standards of coherence (van den Broek et al., 2001).

Experiments 1 and 2 support the extant literature by demonstrating that whereas it is possible for readers to make inferences at test, response times indicate this is a difficult process. It is therefore unlikely that these inferences were made during reading. We propose that the resulting model is not a collection of specific inferences. Rather, certain spatial inferences may be made during reading (e.g., thematic overlays from multiple perspectives; Tversky, 1993), and others may be made in response to testing demands (e.g., novel spatial relationships from a novel perspective). The role of the mental model, then, is to provide a perspective-flexible foundation from which to extract information necessary to generate inferences when needed, and to store any inferences generated during and after reading. This is not to say that spatial mental models do not preserve certain characteristics of the learning format; indeed recent work has demonstrated orientation specificity after route learning during scene recognition (Shelton

& McNamara, 2004), and earlier work demonstrated that map drawing often progresses in a manner corresponding to the landmark ordering in the description (Taylor & Tversky, 1992a). Thus, if the mental model provides this foundation for spatial inferences, working memory processes should also be evoked during test. Note that for consistency we adapt Baddeley's (i.e., 1992) multi-component model terminology to processes involving retrieval from long-term memory. This contrasts with Ericsson and Kintsch's (1995) terminology, which labels working memory processes during retrieval as occurring within "long-term working memory".

While the rationale for working memory processes during spatial mental model application clearly exists, general assessments of working memory at retrieval suggest they may play a lesser role. A number of studies have demonstrated pronounced effects of dual-tasking during learning, but not testing (e.g., Baddeley et al., 1984; Baddeley, Lewis, Eldridge, & Thompson, 1984; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996). This finding is often attributed to relative ease and accessibility of retrieving versus forming memories. Spatial mental models may represent a special case whereby interference may be pronounced during retrieval if the existing model is insufficient to complete a particular memory task. Inference generation may be especially vulnerable to the effects of central and visuospatial interference if spatial mental models cannot be characterized as containing a collection of inferences developed during reading (Graesser et al., 1997).

Our specific experimental hypotheses and rationale are as follows: drawing maps and verifying inference statements should involve a high degree of visuospatial reasoning. Spatial reasoning about environments is likely to recruit visuospatial mechanisms (De Beni et al., 2005; Gyselinck et al., 2007; Lee & Tversky, 2005). Visuospatial secondary tasks should therefore interfere with map drawing and inference statement verification; performance decrements on the latter may be more evident in response times, reflecting the presence of a spatial mental model with the need for retrieval and/or computational time. Articulatory secondary tasks, in contrast, are expected to interfere selectively with declarative information acquired during learning. Thus, an articulatory secondary task should impact verbatim and paraphrased statement verification. These statement types may be best served by a representations of the text itself, suggesting that participants may maintain and directly apply surface and propositional representations when verifying these statement types. Experiment 1 supports this hypothesis, demonstrating faster response times for verbatim and paraphrased, relative to inference statement verification trials. However, if the representations being applied are not verbal in nature, or they are exceedingly easy to retrieve (i.e., Baddeley, Lewis, & Eldridge et al., 1984), articulatory suppression may show no interference effects at retrieval.

The following two experiments also examine secondary task performance. If studies demonstrating pronounced effects of dual-tasking during learning, but not testing (Baddeley et al., 1984; Baddeley, Lewis, & Eldridge et al., 1984; Craik et al., 1996) also apply to spatial description processing, performance decrements may instead be seen with the secondary task (i.e., response slowing, error making; Baddeley et al., 1984; Baddeley, Lewis, & Eldridge et al., 1984; Craik et al., 1996) as a function of the nature of the primary task.

Methods

Participants

Thirty-two Tufts University undergraduates participated for partial course credit, randomly divided into two even groups: 16 for the visuospatial and 16 for the articulatory task. Data from the Experiment 1 control participants comprise the present control group. See Tables 2–4 for several studies that have used identical stimuli and dependent measures; these data demonstrate the reliability of means across dependent measures, experiments, and institutions.

Materials

Materials were identical to those used in Experiment 1.

Procedures

Procedures were identical to those used in Experiment 1 with the exception of secondary task timing.

Secondary tasks. Secondary tasks were used during testing (i.e., statement verification and map drawing), rather than reading. Participants completed statement verification and map drawing using their dominant hand while simultaneously finger tapping with their non-dominant hand. Secondary task performance was recorded via a digital video-recorder during statement verification for assessment of secondary-task rate.

Results

Analysis

Analyses were identical to those of Experiment 1, with the addition of the secondary task rate as an additional dependent measure. For each participant we recorded the number of finger taps (visuospatial) or syllables (articulatory) for each correctly-answered verification statement and divided this number by that trial's response time. These proportions (responses per second) were averaged for each statement type within the two description perspectives.

A total of 64 McNemar χ^2 tests for response bias did not reveal response proportions biased in the "true" direction ($\chi^2_{\max}$ =2.56, all ps > .05).

For all analyses, we confirmed that there was no main effect of or interactions with learning order (survey or route first or second), (all ps > .10, $F_{\max} = 2.03$).

Statement verification: Accuracy

Overall, accuracy results from the statement verification task suggest that whereas spatial mental models are available towards perspective-switching at test, visuospatial resources are necessary towards accurate inference generation at test.

Locative verbatim items: Within- and across-perspective. There was a main effect of statement type, $F(1,45) = 26.97$, $p < .01$, $MSE = .02$. Planned comparisons revealed higher accuracy within- ($M = .94$, $SE = .02$) compared to across-perspectives ($M = .83$, $SE = .02$). This effect replicates Experiment 1 and 2 reduced performance on across- relative to within-perspective study and test trials. There were no other effects for these statement types (Fs < 1).

Verbatim and paraphrased non-locative statements. There were no significant main effects or interactions for these statement types (all ps > .05).

Locative inference statements: Survey and route. There was a main effect of secondary task for these statement types, $F(2,45) = 3.29$, $p < .05$, $MSE = .02$. Planned comparisons revealed higher accuracy in the control group ($M = .86$, $SE = .02$) relative to the visuospatial ($M = .80$, $SE = .03$), $t(30) = 2.28$, $p < .05$, but not the articulatory group ($M = .85$, $SE = .02$), $t(30) = .49$, $p > .05$. There were no other effects for these statement types (Fs < 1).

Statement verification: Response times

Response time results revealed large performance decrements when participants were performing secondary tasks at test, with visuospatial interference during perspective-switching and inferencing, and articulatory interference during declarative memory retrieval.

Locative verbatim items: Within- and across-perspective. As depicted in Fig. 6, there was a main effect of secondary task for these statement types, $F(2,45) = 3.78$, $p < .05$, $MSE = 2.69$. Planned comparisons revealed faster response times in the control group relative to the visuospatial, $t(30) = 2.52$, $p < .025$, and marginally for the articulatory, $t(30) = 2.12$, $p < .05$, group. As in Experiment 1, an effect of statement type revealed faster responses for within- relative to across-perspective study and test trials, $F(1,45) = 337.48$, $p < .01$, $MSE = 1.24$. Further, statement type interacted with secondary task, revealing different performance based on secondary task, $F(2,45) = 10.97$, $p < .01$, $MSE = 1.24$. The visuospatial task interfered primarily with across-, and articulatory with within-perspective, study and test trials. There were no other effects for these statement types (Fs < 1).

Verbatim and paraphrased non-locative statements. There was a main effect of secondary task for these statement types, $F(2,45) = 10.27$, $p < .05$, $MSE = 3.28$. Planned comparisons revealed faster response times in the control group ($M = 4.36$, $SE = .39$) relative to the articulatory ($M = 5.63$, $SE = .31$), $t(30) = 3.69$, $p < .01$, but not the visuospatial ($M = 4.44$, $SE = .28$), $t < 1$,

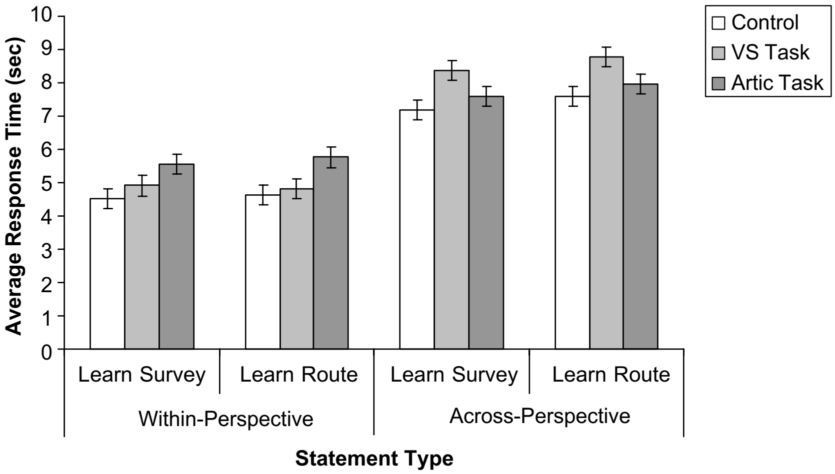

Fig. 6. Experiment 3 mean response time and standard error on the statement verification task for locative verbatim items, within and across perspectives, and following survey and route learning. Results are displayed by secondary task group.

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group. There were no other effects for these statement types (Fs < 1).

Inference survey and route statements. There was a main effect of secondary task, $F(2,45) = 9.21$, $p < .01$, $MSE = 4.43$. Planned comparisons revealed faster response times in the control group ($M = 7.31$, $SE = .51$) relative to the visuospatial ($M = 8.83$, $SE = .34$), $t(30) = 3.6$, $p < .01$, but not the articulatory ($M = 7.64$, $SE = .33$), $t(30) = .77$, $p > .05$, group. There were no other effects for these statement types (Fs < 1).

Secondary task performance

See Table 5 for visuospatial and articulatory secondary task performance for each of the six statement types. Differences in secondary task performance were only seen for the locative verbatim items (within- and across-perspective). Participants tapped more slowly during across-, relative to within-perspective statement verification, $F(1,15) = 14.07$, $p < .01$, $MSE = .02$. In contrast, articulatory rates were marginally slower during within-perspective, relative to across-perspective statement verification, $F(1,15) = 3.86$, $p < .10$, $MSE = .02$.

Table 5
Experiment 3 average visuospatial (taps/s) and articulatory secondary task performance (syllables/s), for each of the six statement verification types and two study perspectives

Task & statement type	Study perspective			
	Survey		Route	
	M	SE	M	SE
Visuospatial task				
Locative				
Within-perspective	1.52	.034	1.48	.039
Across-perspective	1.37	.047	1.39	.039
Non-locative				
Verbatim	1.56	.058	1.58	.063
Paraphrased	1.60	.048	1.52	.050
Locative inference				
Inference survey	1.32	.046	1.34	.051
Inference route	1.29	.043	1.30	.049
Articulatory task				
Locative				
Within-perspective	.825	.036	.819	.040
Across-perspective	.914	.028	.898	.041
Non-locative				
Verbatim	.838	.048	.787	.049
Paraphrased	.796	.045	.809	.044
Locative inference				
Inference survey	.897	.037	.816	.041
Inference route	.921	.046	.862	.032

Map drawing

There were no significant main effects or interactions for any of the map drawing dependent measures (all ps > .05; see data in Table 6).

Discussion

One major goal of the present experiment was to assess the extent to which spatial mental models formed from survey and route description reading would allow for direct inference retrieval. The present results support our prediction that, whereas mental models are generally formed during spatial description reading, these models do not necessarily contain a collection of retrievable inferences. Rather, manipulating these models towards inference generation occurs when testing circumstances demand such processes. Further, these mental models are complemented by the retention of relatively coarse surface features of the text, as suggested by map drawing patterns (Taylor & Tversky, 1992a) and recent work with spatial descriptions and videos (Shelton & McNamara, 2004). We review these results below, in turn, by secondary task.

Visuospatial suppression during statement verification consistently and selectively interfered with inferencing times, and inconsistently with inferencing accuracy, relative to the control group. These results suggest that participants are forming perspective-flexible mental models during reading, but these models do not support direct inference retrieval. Rather, they serve as a foundation for deriving the information necessary for making inferences. Statement verification involving inferencing about spatial environments appears to involve visuospatial mechanisms; this effect was most consistent in response time.

Table 6
Experiment 3 means and standard errors for the three map scoring procedures, by study perspective and secondary task

Measure and group	Study perspective			
	Survey		Route	
	M	*SE*	*M*	*SE*
Landmark recall				
Control	.906	.029	.885	.032
Visuospatial	.911	.025	.875	.032
Articulatory	.891	.026	.864	.038
Relative landmark locations				
Control	.959	.020	.916	.030
Visuospatial	.899	.024	.934	.021
Articulatory	.913	.023	.926	.024
Quadrant accuracy				
Control	.973	.023	.963	.018
Visuospatial	.959	.016	.949	.018
Articulatory	.968	.017	.960	.017

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Articulatory suppression interfered only when participants could rely upon surface or propositional forms, which appear to be retained and easily used across short study-test intervals. That is, the mental models coexist with declarative surface or proposition representations; these relatively superficial memory traces are likely to decay with time, however (e.g., Kintsch, Welsch, Schmalhofer, & Zimny, 1990). Neither the visuospatial or articulatory tasks interfered with map drawing. Because participants have a relatively long time to draw their maps, map drawing may be more amenable to task-switching between primary and secondary tasks, or alternatively the present secondary tasks may not share response competition demands (i.e., Hegarty, Shah, & Miyake, 2000).

Secondary task performance showed slowed tapping speed during inferencing, but slowed syllable articulation during non-inference statement verification. These results further implicate visuospatial and articulatory processes during retrieval and support the notion of separable processing mechanisms within working memory. Finally, we extend earlier work demonstrating secondary task slowing due to resource competition at retrieval (Craik et al., 1996; Richardson & Baddeley, 1975).

Overall, results support the event indexing model (Zwaan et al., 1995; Zwaan & Radvansky, 1998), constructivist spatial mental model and cognitive collage theory (Schneider & Taylor, 1999; Tversky, 1991, 1993; van Dijk & Kintsch, 1983), and work noting the importance of multiple discourse variables in determining whether inferences will be formed during reading (e.g., de Vega, 1995; Jahn, 2004; Levine & Klin, 2001; McKoon & Ratcliff, 1992; Rapp & Taylor, 2004; Zwaan & Radvansky, 1998). The event indexing model predicts mental model construction during reading; the present experiment supports this theory by demonstrating only minimal interference of visuospatial suppression on inferencing accuracy and map drawing, and similar accuracy rates and response times for within- and across-perspective inference. The present results also demonstrate retention of *both* the text itself as evidenced by selective articulatory interference at test, and the spatial mental model as evidenced by inferencing without a cost of switching perspectives from learning to test. While we (and most other work) used a relatively brief study-test retention interval, with time the availability of coarse information directly conveyed by the text may become relatively limited.

Experiment 4

Our final experiment investigates the interference of two central executive tasks at testing, random generation and sequence monitoring. The random generation task appears to tap multiple executive processes, in particular those involved in monitoring and maintaining goal-directed strategies. These same resources appear to be recruited during the integration and manipulation of verbal and visuospatial information within working memory. However, with spatial mental models already developed, at test we expect random generation to interfere with inferencing times, more so than with accuracy.

The sequence monitoring task requires continuous updating of sequential representations within working memory, much like those processes occurring during route description reading. In contrast to Experiment 2, however, we do not expect sequence processing to interfere with inferencing following either route or description reading. This hypothesis is based on the notion that abstracted mental models may not preserve the format of the learning medium (i.e., Taylor & Tversky, 1992a; Tversky, 1993; van Dijk & Kintsch, 1983). However, if route descriptions are stored and accessed with reliance upon their intrinsic sequencing, as suggested by map drawing and recent work with scene recognition (Shelton & McNamara, 2004), then this should become apparent during testing with sequence interference.

Finally, secondary task performance, operationalized as tapping speed and degree of randomness for random generation, and accuracy for sequence monitoring, should parallel any performance decrements seen during statement verification.

Methods

Participants

Thirty-two Tufts University undergraduates participated for partial course credit, randomly divided into two groups: 16 for the random generation task, and 16 for the sequence monitoring task. Data from Experiment 1 control participants comprise the present control group. See Tables 2–4 for several studies that have used identical stimuli and dependent measures; these data demonstrate the reliability of means across dependent measures, experiments, and institutions.

Materials

Materials were identical to those used in Experiment 2.

Procedures

Procedures were identical to those used in Experiment 2 with the exception of secondary task timing.

Secondary tasks. Secondary tasks were used during testing (i.e., statement verification and map drawing), rather than reading. Participants used their dominant hand for statement verification and map drawing, and their non-dominant hand for random finger tapping and recording of target identification. Secondary task performance was recorded via a digital video-recorder during statement verification.

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Results

Analysis

Analyses were done in an identical manner to those of Experiment 2, with the addition of secondary task performance as a dependent measure. For all analyses, we confirmed that there was no main effect of or interactions with learning order (survey or route first or second), (all ps $> .10$, $F_{\max} = 1.82$).

Random generation. The addition of video-recorded secondary task performance in the present experiment allowed us to measure both speed and randomness during random finger tapping. Speed was calculated as in Experiment 3.

We used the RGCalc software (Towse & Neil, 1998) to calculate the Evans' Random Number Generation Index (RNG; Evans, 1978); the RNG assesses the relative frequency of diagram combinations, with higher scores (range 0–1) indicating less randomness. To increase index reliability and account for a low number of overall trials (and thus taps) we collapsed across statement types in the following manner: inference statements and across-perspective verbatim locative statements (also inferences) were combined within each learning perspective to form a single *inference* measure, and verbatim locative (within-perspective), non-locative (verbatim and paraphrased) were combined within each learning perspective to form a single *non-inference* measure. An RNG index score was calculated for each participant's tapping performance for inference and non-inference statement types within each description perspectives. Analysis of RNG data was done using a 2(study perspective: survey, route) × 2(statement type: inference, non-inference) ANOVA.

Sequence monitoring. Monitoring performance was measured as accuracy in responding to target sequences (three successive beeps in left ear), and false alarm rates. Targets were only considered as such when the complete target string (three successive left beeps) occurred during a given verification trial. Target identification accuracy was calculated for each statement type as the number of target identifications relative to the total number of targets presented. False alarm rates were calculated by summing the number of false alarms that occurred during each statement type.

Statement verification: Accuracy

A total of 64 McNemar χ^2 tests for response bias did not reveal response proportions biased in the "true" direction ($\chi^2_{\max} = 2.32$, all ps $> .05$). Overall, there was no evidence for central executive interference within the statement verification accuracy data.

Locative verbatim items: Within- and across-perspective. There was a main effect of statement type, $F(1,45) = 20.65$, $p < .01$, $MSE = .02$, with higher accuracy within- ($M = .94$, $SE = .02$) rather than across-perspectives ($M = .85$, $SE = .02$). There were no other effects for these statement types (Fs < 1).

Verbatim and paraphrased non-locative statements. There were no significant main effects or interactions for these statement types (all ps $> .05$).

Inference survey and route statements. There were no significant main effects or interactions for these statement types (all ps $> .05$).

Statement verification: Response times

As with accuracy, there was little evidence for response time differences as a result of central executive interference.

Locative verbatim items: Within- and across-perspective. As depicted in Fig. 7, an effect of statement type, $F(1,45) = 221.78$, $p < .01$, $MSE = 1.86$, revealed faster response times within- rather than across-perspectives. There were no other effects for these statement types (Fs < 1).

Verbatim and paraphrased non-locative statements. There were no significant main effects or interactions for these statement types (all ps $> .05$).

Inference survey and route statements. A marginal effect of secondary task, $F(2,45) = 2.66$, $p < .10$, $MSE = 4.84$, suggested faster response times in the control ($M = 7.31$, $SE = .51$) relative to the random generation group ($M = 8.21$, $SE = .36$); this difference was marginally significant in an independent-samples t-test, $t(30) = 2.05$, $p < .10$. There were no other effects for these statement types (Fs < 1).

Secondary task performance: Random generation

See Table 7 for random generation task performance for each of the six statement types. See Fig. 8 for average RNG scores for study perspectives and statement types (inference, non-inference); recall that higher RNG scores reflect less randomness. In line with the notion that inference generation is more cognitively demanding following route versus survey learning, an effect of study perspective, $F(1,15) = 9.88$, $p < .01$, $MSE = .003$, revealed higher RNG scores following route relative to survey learning. An effect of statement type, $F(1,15) = 122.66$, $p < .01$, $MSE = .002$, revealed higher RNG scores during inference statements relative to non-inference statements. Finally, a study perspective by statement type interaction, $F(1,15) = 7.75$, $p < .05$, $MSE = .002$, revealed that RNG score differences

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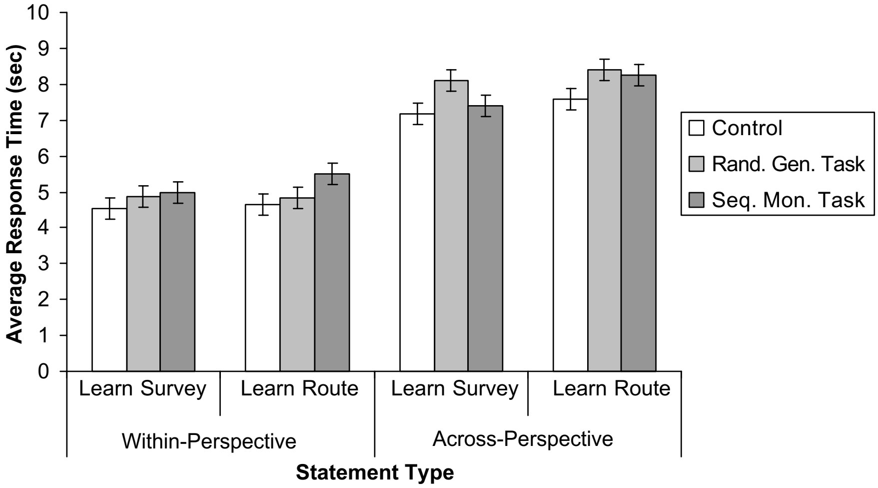

Fig. 7. Experiment 4 mean response time and standard error on the statement verification task for locative verbatim items, within and across perspective, and following survey and route learning. Results are displayed by secondary task group.

Table 7
Experiment 4 average random generation secondary task performance (taps/s), for the two study perspectives and each of the six statement verification types

Task & statement type	Study perspective			
	Survey		Route	
	M	*SE*	*M*	*SE*
Locative				
Within-perspective	.98	.047	.97	.033
Across-perspective	.92	.055	.89	.059
Non-locative				
Verbatim	1.03	.066	.98	.048
Paraphrased	.99	.042	.94	.042
Locative inference				
Inference survey	.91	.065	.92	.059
Inference route	.96	.043	.98	.066

between survey and route learning were driven by inferencing, $t(15) = 4.52$, $p < .01$, as non-inferencing trials showed no study perspective differences, $t(15) = .83$, $p > .05$. There were no significant main effects or interactions for tapping speed (all $ps > .05$).

Secondary task performance: Sequence monitoring

See Table 8a for mean proportion of targets identified and Table 8b for false alarm rates during sequence monitoring; overall, sequence monitoring performance was high ($M = .915$, $SE = .01$); an omnibus ANOVA revealed no sequence monitoring performance differences as a function of study perspective, $F(1, 15) = .03$, $p > .05$, $MSE = .02$, or statement type, $F(5, 75) = .51$, $p > .05$, $MSE = .02$. The average number of false alarms was very low ($M = 1.92$, $SE = .17$), and did not vary by study perspective or statement type.

Map drawing

There were no significant main effects or interactions for any of the three map scoring procedures (all $ps > .05$).

Discussion

As with Experiment 3, secondary tasks at test impacted statement verification time more so than accuracy. Statement verification accuracy was not affected by random generation, but led to marginally slower response times. More interestingly, verification statements requiring inferencing impacted random generation performance. Inferencing reduced the randomness of participant-generated finger taps, particularly following route relative to survey description study. These results suggest three main points: first, central executive interference may produce minor delays in decision making while leaving accuracy intact. This result is congruent with work demonstrating relatively diminished effects of secondary tasks on primary task performance at retrieval (Baddeley et al., 1984; Baddeley, Lewis, & Eldridge et al., 1984; Craik et al., 1996; Pazzaglia et al., 2007), and extends it to random generation tasks. Second, inferencing based on route descriptions may induce a higher working memory load, relative to survey description inferences; this result is in line with the notion that route descriptions may be cognitively demanding formats for acquiring spatial mental models (Brunyé & Taylor, 2007; Lee & Tversky, 2005; Noordzij & Postma, 2005; Noordzij, Zuidhoek, & Postma, 2006; Shelton & McNamara, 2004). We also provide support

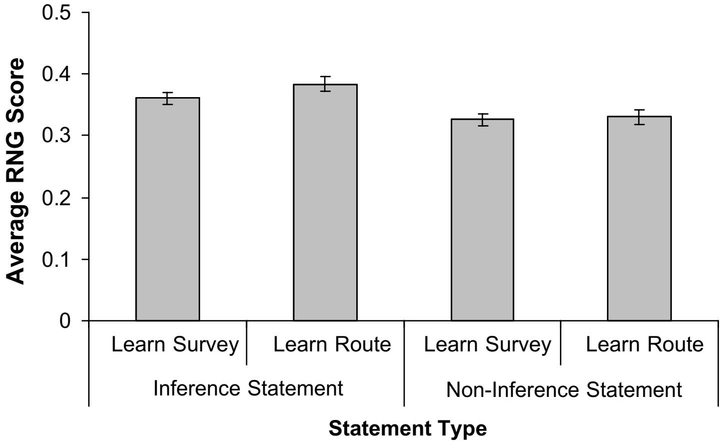

Fig. 8. Experiment 4 mean RNG scores for the two study perspectives (route, survey) and statement types (inference, non-inference); recall that higher RNG scores reflect less randomness.

Table 8a
Experiment 4 average sequence monitoring secondary task performance (identified targets/total targets), for the two study perspectives and each of the six statement verification types

Task & statement type	Study perspective			
	Survey		Route	
	M	*SE*	*M*	*SE*
Locative				
Within-perspective	.93	.037	.90	.032
Across-perspective	.89	.035	.94	.025
Non-locative				
Verbatim	.92	.032	.93	.052
Paraphrased	.91	.043	.90	.035
Locative inference				
Inference survey	.94	.027	.92	.030
Inference route	.91	.043	.89	.035

Table 8b
Experiment 4 cumulative frequency of false alarms during the sequence monitoring secondary task, for the two study perspectives and each of the six statement verification types

Task & statement type	Study perspective	
	Survey Cum. Freq.	Route Cum. Freq.
Locative		
Within-perspective	2	2
Across-perspective	1	2
Non-locative		
Verbatim	2	2
Paraphrased	3	2
Locative inference		
Inference survey	2	3
Inference route	2	1

for general discourse processing models, such as event-indexing (i.e., Zwaan et al., 1995; Zwaan & Radvansky, 1998), which predict mental model development during reading; the present results support this notion following both survey and route learning.

Finally, we have demonstrated the utility and specificity of secondary tasks targeting particular central executive roles, and with central executive processing the importance of examining primary tasks that demand both verbal and spatial working memory mechanisms (i.e., Hegarty et al., 2000; Miyake et al., 2001). The sequence monitoring task assessed the sequential nature of eventuating mental models following route description learning. Recent work has suggested central executive involvement in the monitoring and updating of sequential representations, and temporal tagging, within working memory (Brunyé et al., 2006; Miyake & Shah, 1999; Miyake et al., 2000). Other work has suggested that the memories formed from route descriptions may maintain a principle reference vector defined by the first route path, and may be applied to map drawing in a sequential manner (Shelton & McNamara, 2004). The present experiment demonstrated that the inherent sequential nature of route descriptions is not necessarily maintained in eventuating mental representations; that is, whereas readers may track the sequential nature of route descriptions during reading, this information may not be used towards inferencing or map drawing. Note, however, that map drawing may be relatively amenable to task switching, reducing our ability to find sequential interference effects at test. These results suggest the importance of temporal-sequential information during route description processing towards the *development,* but not necessarily the application, of cohesive mental models.

General discussion

To our knowledge, the present study represents the first experimental examination of visuospatial, articulatory, and central executive working memory involvement in spatial discourse reading, and later testing. We provide evidence that each of these processes is differentially involved during spatial description processing. The articulatory rehearsal loop plays a large role in acquiring information from descriptions, in this case both route and survey perspective descriptions. These results support the notion that while readers construct situation models during reading, a lower-level scaffold for these models is the propositional base (i.e., Kintsch et al., 1990; van Dijk & Kintsch, 1983). Interference with articulatory mechanisms during reading appears to restrict propositional base formation and therefore the ability for readers to acquire both declarative memories and mental models (see also Canas et al., 2003; De Beni et al., 2005; Gyselinck et al., 2007). Visuospatial mechanisms are generally involved during spatial description reading, and particularly in route description reading; they also appear to be involved when participants apply spatial memories to make inferences. These findings support Baddeley's (1992) conceptualization of visuospatial function, as well as a number of recent findings (De Beni et al., 2005; Deyzac, Logie, & Denis, 2006; Pazzaglia et al., 2007), and demonstrate limitations on the degree to which inferences are generated during reading (e.g., Levine & Klin, 2001). Finally, the central executive plays an important role in the development of spatial mental models, and using these models towards inferencing tasks. These results support recent dual-task work (i.e., Baddeley et al., 1998; Brunyé et al., 2006), and provide clear support for an emerging consensus that multi-component models of working memory have clear theoretical relevance to research in language comprehension and memory (i.e., Baddeley et al., 1998; De Beni et al., 2005; Miyake et al., 2001; Pazzaglia et al., 2007).

The present experiments also provided a unique opportunity to examine the comprehension processes involved during spatial description reading. Readers process spatial descriptions at a level beyond the propositional base; spatial information is tracked during reading toward the development of rich spatial memories. This is in contrast to findings demonstrating limited tracking of the spatial dimension during narrative comprehension (Radvansky & Copeland, 2000; Zwaan, Magliano, & Graesser, 1995), but congruent with the notion that such characteristics will be tracked when easy to do, tied to functional relevance, or needed for local and global coherence (Estevez & Calvo, 2000; Levine & Klin, 2001; Linderholm & van den Broek, 2002; Magliano et al., 2001; Morra, 2001; Morrow, 1994; Radvansky & Copeland, 2006a, 2006b; Rinck et al., 1997; Taylor et al., 1999; van den Broek et al., 2001). The functional relevance of spatial information for spatial descriptions is clearly high. For route descriptions, in particular, readers appear to recruit significant visuospatial and central resources towards mentally simulating travel (i.e., Pazzaglia et al., 2007; Zwaan, 1999). This finding lends support for discourse models proposing that readers actively track multiple text dimensions towards mental model development (Zwaan & Radvansky, 1998), and relatively limited support for memory models suggesting that resonance of propositional information is sufficient for text comprehension (Myers & O'Brien, 1998; O'Brien & Myers, 1999). The present results support an active interpretive process during reading that incorporates both propositional features of the text *and* spatial imagery developed by the reader in an effort to mentally simulate the environment and develop an accurate mental model (Bransford et al., 1972; Pazzaglia et al., 2007; Zwaan, 1999).

Mental models formed from spatial descriptions appear to be abstractions that support perspective switching and inferencing. These models appear to recruit articulatory mechanisms towards direct retrieval, and visuospatial and central mechanisms towards inference generation. This supports work suggesting that readers form limited inferences during reading (Levine & Klin, 2001), and supports and extends recent work with spatial descriptions (Pazzaglia et al., 2007). Spatial mental models clearly provide the flexibility to support perspective switching and inferencing, but may not be completely dissociated from the learning materials. This feature of spatial mental models was evident when secondary task effects on testing interacted with learning format; to the extent that spatial mental models are fully abstracted from the learning materials, such an interaction would not be seen. We suggest that in line with recent work using the same descriptions, and virtual environment analogues, spatial memories preserve some features of the initial learning formats—for instance, orientation specificity towards a principle reference vector (Shelton & McNamara, 2004). We propose that larger study-test lags and substantial overlearning may reduce some of these effects, diminish memory for surface characteristics of the text, and further abstract the resulting spatial mental model (Brunyé & Taylor, 2007; see also Tversky, 1991, 1993).

Limitations

One possible interpretation of our results is that there are limited global resources allocated to all working memory processes; another interpretation is that each subsystem draws from a limited allocation of a common pool, or uses its own limited resource pool. Under the

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first explanation visuospatial interference, for example, can potentially detract from articulatory mechanisms, and lead to verbal learning decrements. The present experiments did not find evidence for this; it is unclear if this is a reflection of resource allocation within working memory or the degree to which our secondary and primary tasks were (or were not) cognitively demanding. These issues are currently being examined (e.g., Fedorenko, Gibson, & Rohde, 2007; Lovett, Reder, & Lebiere, 1997; Young & Lewis, 1999).

The present results do not allow us to determine whether spatial mental models are computed or recruited during test. That is, to the extent that spatial mental models are in fact developed during reading they will be used at test for certain processes, such as inferencing. However, spatial mental models may be computed upon demand (i.e., at test) rather than during reading, especially when the reading material is cognitively demanding. It is our view that spatial mental models likely arise out of the interactions of spatial and verbal information during *both* learning and testing. That is, whereas certain inferences may be generated and a mental model of the environment developed during reading, testing circumstances likely reinforce, modify, and expand upon these initial models. To the extent that participants can make across-perspective inferences with similar accuracy and response times, we feel that a mental model is available. Recent work looking at the progression of spatial mental models over time has demonstrated that these models are available after as little as a single reading of survey, but not route descriptions (Brunyé & Taylor, 2007); these results correspond well with the present findings. Of course, the question remains open as to whether the models are ready to be computed, or ready to be used, at test.

Applying narrative discourse theory to spatial discourse experiments has obvious limitations. Narrative discourse rarely focuses almost exclusively on spatial information, instead spatial information becomes a focus with a spatial shift (i.e. character moves from one room to another), for example. In spatial descriptions, spatial information is the primary focus and is typically comprised of explicitly stated and/or inferred spatial relationships. Further, in narrative discourse temporal-sequential information is inevitable whereas in spatial descriptions is it conveyed from route, but not survey, descriptions. It is not our intention to explicitly compare and contrast the applicability of narrative discourse theories to spatial discourse comprehension. Rather, we feel that general discourse theory provides an informative foundation for developing hypotheses and interpreting our results. Ultimately theories of expository discourse comprehension will likely emerge, and we feel the present studies take a substantial step in this direction.

Concluding remarks

Spatial descriptions are an exceedingly common discourse format with its own set of characteristics, demands, and eventuating mental model properties. Finding our way or informing others where to go, or what an environment is like, requires a complex interplay of visuospatial, articulatory, and central executive processes. Perhaps the most impressive aspect is the harmonious interactions of these processes that result in our ability to form flexible spatial memories, and use them with ease and convenience towards accurate solutions to complex problems.

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