Switching between environmental representations in memory

James R. Brockmole*, Ranxiao Frances Wang

Department of Psychology, University of Illinois, Urbana-Champaign, 603 E. Daniel Street, Champaign, IL 61820, USA

Abstract

In everyday life we accomplish tasks that require the storage and access of mental representations of different environments that we are not currently perceiving. Past research has suggested that environments are encoded by a series of independent representations that are organized in memory. Three experiments tested this idea further by asking whether multiple representations of environments can be accessed simultaneously. Using a cued task-set switching paradigm, subjects judged spatial relationships between target locations in two familiar environments. Response times were longer when successive trials probed different environments, an effect not due to switching between semantic categories or semantic priming, suggesting that representations of environments are accessed sequentially. Implications for various hypotheses concerning the properties of environmental representations are discussed. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Switching; Environmental representations; Memory

1. Introduction

In everyday life we must accomplish tasks based upon our knowledge of environments we are not currently perceiving. For example, we can give directions to our house to a friend or we can tell a student where a particular set of journals is in the library while we sit in our office. We must maintain representations of such relationships in the environment which we then use on demand. These representations are largely veridical (e.g. Baird, Merrill, & Tannenbaum, 1979; Baum & Jonides, 1979), and flexible enough to enable spatial judgments to be made about locations that have never been directly experienced (e.g. Levine, Jankovic, & Palij, 1982). Thus, to make spatial judgments effectively, there

---

* Corresponding author. Tel.: +1-217-244-8538; fax: +1-217-244-5876.
  E-mail address: jbrockmo@s.psych.uiuc.edu (J.R. Brockmole).

are two features of the environmental representation system that must be balanced: storage and computation.

Past analysis of environmental knowledge has pointed out that the trade-off between storage and computation would be mediated if the environment is systematically broken down into smaller chunks, each of which is encoded by a separate representation (McNamara, 1986). That is, if we have separate representations of a room, the building the room is in, the block the building is on, and so forth, we only need to consider the relevant local aspects of the overall environment at one time. If the representations are organized into a systematic structure, then spatial judgments that span individual representations can be derived by accessing the appropriate representations and computing a solution. Research over the past two decades has supported such a view in a variety of spatial contexts. The dominant current view is that the organizational structure linking mental representations of environments is hierarchical, such that representations occupy distinct levels in an overall tree-like structure (Hirtle & Jonides, 1985; Huttenlocher, Hedges, & Duncan, 1991; McNamara, 1986; McNamara, Hardy, & Hirtle, 1989; Stevens & Coupe, 1978; Taylor & Tversky, 1992a; Wilton, 1979).

1.1. The structure of environmental representations in memory

The hierarchical organization of environmental representations in memory has been inferred from retrieval patterns observed when recalling spatial relationships or making spatial judgments about environmental layouts. For example, in the seminal paper on hierarchical representations of environments, Stevens and Coupe (1978) demonstrated that people make systematic errors in judging spatial relationships among locations housed in what they called different "political units". For example, in their experiments, subjects overwhelmingly judged Reno, Nevada to be north*east* of San Diego, California although Reno is actually north*west*. They accounted for this distortion by arguing that the spatial relationship between two locations is explicitly encoded only if the locations are stored within the same unit, and that the relationship between two locations encoded in separate units must be derived by combining within-unit and between-unit information. Thus, the superordinate knowledge that Nevada is east of California was combined with subordinate knowledge that San Diego is in southern California and Reno is in northern Nevada, resulting in the biased judgment.

Similar biases were also shown by McNamara (1986) in smaller scale novel environments. By dividing a room into different regions, he showed that direction estimates between items in the room were influenced by knowledge of the spatial arrangement of the regions in which the items were located. For example, for items in regions that shared a north–south relationship, direction estimates tended to be biased toward the north–south axis of space. Conversely, if the regions shared an east–west relationship, direction estimates were biased toward this axis. Apparently, making spatial judgments about items in different regions, despite being in the same room, required the computation of information stored in different representations.

The hierarchical organization of different environmental representations in memory has also been indicated by a variety of other retrieval patterns observed when recalling or making spatial judgements about environmental layouts. For example, free recall of envir-

onments, whether verbal (Hirtle & Jonides, 1985; McNamara et al., 1989) or pictorial (Taylor & Tversky, 1992a), unfolds in an orderly unit-by-unit sequence. Furthermore, spatial judgments among targets within a single unit are made faster than across-unit judgments (McNamara, 1986; Wilton, 1979), regardless of the Euclidean distance between the target locations. This suggests that within-unit locations share a greater degree of "mental closeness". This conclusion was further supported by the observation that, when making distance judgments, distances between within-unit items are underestimated while across-unit judgments tend to be overestimated (Hirtle & Jonides, 1985; McNamara, 1986).

Some research has also addressed the question of what a "unit" is, and how units are established. Several studies showed that divisions between environmental units can be determined either by explicit borders (e.g. McNamara, 1986; Stevens & Coupe, 1978) or subjective boundaries imposed by individual subjects (e.g. Hirtle & Jonides, 1985; McNamara et al., 1989; Taylor & Tversky, 1992a). In either case, these divisions are based upon factors such as size, spatial arrangement, functional importance, and/or semantic similarity. Thus, the organization of representational units is referred to as hierarchical because units encoding more detailed information (e.g. a room) are seemingly "part of" units containing broader environmental information (e.g. a building).

1.2. The current investigation

One of the most fundamental properties of environmental memory espoused by hierarchical theories is that people maintain multiple representations of various environments in memory. Given the evidence for multiple representations, some important questions arise about how information housed in separable representations is processed. The question of particular interest here concerns the manner in which information about environments is *accessed* from memory. That is, if our world is parsed into multiple representations that are individually maintained in a memory system, are we able to access spatial knowledge of different environments at the same time? For example, if a room and the building the room is in are represented separately, can knowledge of the location of objects inside the room and other places inside the building be accessed in unison, as if one can "see" the whole entity through the walls in the mind's eye? If so, then it should be possible to switch between different environments freely in order to make spatial judgments about objects located in separate environments. Alternatively, if separate representations must be serially accessed, whenever a switch between, or consideration of, multiple environments is required while making a spatial judgment an additional process (such as inhibition of the currently active representation and activation of the new representation) would be required. For example, the bias effects reported by both McNamara (1986) and Stevens and Coupe (1978) may have resulted from a process that analyzed both representations together if both can be accessed simultaneously, or from one that considered each in turn if they are not active at the same time.

The present studies used a spatial directional judgment task so that the nature of representational access could be observed. In this task subjects were simply required to indicate whether two real-world target locations were presented in the correct spatial relationship to each other. This task has an advantage over previous studies which argued

for hierarchical structure by demonstrating that map drawing and verbal or written descriptions of an environment proceed in an organized, section-by-section sequence. These later behavioral measures are bound by rules of orderly communication which themselves often demand a linear or hierarchical structure. Thus, it is possible that behavioral effects observed in these tasks attributed to the representations themselves are the result of a specific retrieval/production process, rather than an intrinsic property of the representation per se. For example, even if one can access multiple environments at the same time, one can only report one at a time. Thus, evidence for simultaneous access of multiple representations may be obscured in a verbal or map drawing task. On the other hand, a spatial judgment task has no intrinsic demand for hierarchical structure; thus, the behavioral pattern should reveal the nature of the representations and processes.

To obtain evidence for simultaneous or sequential access of environmental representations, the spatial judgment task was nested within a cued task-switching paradigm (e.g. Allport, Styles, & Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995; Spector & Biederman, 1976). The cued task-set switching methodology hinges on the comparison of response times (RTs) when subjects either do or do not have to change the cognitive representation or processor between successive judgments. For example, if a sequence of judgments relies on the same cognitive structure, RTs should be fast. Alternatively, if successive judgments rely on different cognitive systems that do not remain active at the same time, then a switch between these systems would be necessary, causing responses to be slowed. In the present experiments, subjects made judgments about the spatial relationships among target locations within two familiar local environments (e.g. a building and a room within that building), presented in a random order. Thus, each trial probed either the same environment as the preceding trial (no-switch trials), or a different environment (switch trials). If judgments corresponding to each environment involve the access of separate representations, and if only one representation can be accessed at a time, then one would expect longer reaction times in the switch trials than in the no-switch trials because it should take some time to change the active representation. On the other hand, if the representations of the two environments can be accessed simultaneously (i.e. both representations are active at the same time), then there would never be a need to switch representations and reaction times should therefore be the same in switch and no-switch trials.

Thus, comparison of reaction times between the switch trials and no-switch trials can shed light on the processes involved in accessing these representations. If the time to make judgments is greater following a shift in the probed environment, then it can be inferred that the representations of each environment in memory are retrieved one at a time, and cannot be simultaneously maintained in working memory. In this case, subjects are simply unprepared to address one environment while considering the other. When a switch occurs, the inactive representation must be retrieved, a process which takes time. This conclusion is strengthened if a pre-cue indicating the identity of the upcoming environment reduces the switch cost as it allows subjects time to switch representations prior to the start of the trial (e.g. Biederman, 1973; Sudevan & Taylor, 1987). If switch costs are absent, however, it must be inferred that the two environments can be processed jointly.

The use of environments highly familiar to our participants through daily navigation contrasts with research on environmental representations in humans which has primarily

tested human performance within fictional or novel environments. Although the use of novel environments controls for experience and prior knowledge, it seems possible that the way in which novel and familiar environments are encoded in memory may differ. For example, people may construct separate local representations for the novel space which are independent of each other and accessed separately immediately after learning. Indeed, in initial spatial learning, local representations appear to be viewpoint-dependent as novel views of learned environments are difficult to recognize (Diwadkar & McNamara, 1997). However, over time these representations may be combined into a more holistic structure. For example, after navigating from room to room over and over again one may eventually become able to access spatial knowledge of the entire building simultaneously.

Support for the hypothesis that repeated navigation generates a more complete representation is found in research with animals. During navigation, if the animal is restricted in its exploration of the environment (e.g. gains experiences with different areas, but not their interconnections), it builds separate representations of the restricted spaces and initially has difficulty combining information from these representations (e.g. Ellen, Parko, Wages, Doherty, & Herrmann, 1982; Mazmanian & Roberts, 1983; Sutherland, Chew, Baker, & Linggard, 1987). However, given the opportunity to experience the connections or associations among these locations, over time animals are able to integrate once independent pieces of information (e.g. Ellen, Soteres, & Wages, 1984) and navigate well through an environment initially learned in a piecemeal fashion. From these results it has been argued that animals combine related representations as they gain more experience with the environment (Poucet, 1993). Thus, using familiar environments maximized the chance of finding evidence for simultaneous access of multiple environmental representations. A finding of sequential access, then, can be generalized to both novel and familiar environments.

2. Experiment 1

In Experiment 1, subjects imagined themselves in specified locations within familiar environments facing a particular direction. The sequence of events in each trial is illustrated in Fig. 1. For each trial, one target location was presented at one of eight equally spaced positions around the perimeter of a circle which represented the 360 degrees of space surrounding the subject (e.g. the top position represented the area of space directly in front of the subject, etc.). Dot placeholders were used to mark the positions not currently probed in the imagined environment. Subjects indicated whether the target was presented in the proper spatial position with reference to the subject's imagined location and orientation.

Targets were selected from two related environments. In a continuous sequence of trials, both environments were probed in random order. Thus, a trial either probed the same (no-switch trial) or a different (switch trial) environment as the preceding trial. A valid cue indicated from which environment the target would be drawn and appeared immediately following the subject's response on the previous trial. Then after a delay (i.e. cue-to-target interval, or CTI) the target appeared. The CTI was either 0 ms (simultaneous onset) or 2000 ms.

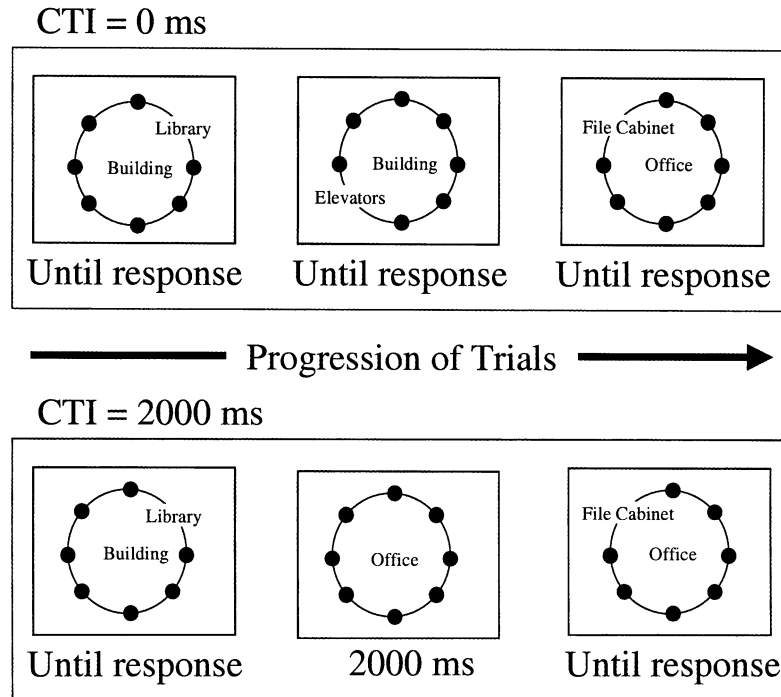## CTI = 0 ms

Progression of Trials

CTI = 2000 ms

Fig. 1. Schematic illustration of the procedure used in Experiments 1 and 2. Experiment 3 was identical in its procedure, save that the office targets were replaced by campus targets.

Retrieving a new representation is a process that requires time. As such, if the mental representation of each environment must be retrieved each time a change in the probed environment occurs, then RTs should incur a cost when switches are required. Additionally, this cost should vary as a function of the CTI as longer delays afford more time to switch representations prior to the onset of the target. Alternatively, if the environments are drawn from a single representation, or if two environmental representations can be retrieved or processed simultaneously, switching the probed environment should have no effect on RT because no extra time would be required to retrieve a new representation.

An additional (although subsidiary) factor of interest was whether switch costs, should they be observed, vary depending on the direction of the switch. This question is most relevant within the framework of hierarchical organization, as one of the probed environments can be considered "superordinate" to the other (e.g. a building and a room within the building). Differences in the switch cost would be observed, for example, if retrieval of lower level representations entails the retrieval of higher level representations, but retrieval of higher levels does not entail the retrieval of lower levels. Such an outcome would be consistent with the previously described bias effects where judgments at the subordinate levels were influenced by the superordinate representation, but not vice versa (e.g. McNamara, 1986; Stevens & Coupe, 1978).

In Experiment 1, psychology professors at the University of Illinois made judgments

about locations within the psychology building and their individual office within the building. At the University of Illinois, the psychology building surrounds a central interior atrium. On trials which probed building locations, subjects imagined themselves being in the center of this atrium (and hence the building as a whole). On trials which probed office locations, subjects imagined themselves in the center of their respective offices. To avoid potential time costs associated with changes in geographical perspective, subjects were told to imagine facing west in both environments.

2.1. Method

2.1.1. Subjects

Six professors at the University of Illinois (mean age of 43 years) participated after providing informed consent. To ensure a high level of familiarity with each environment, all subjects were on faculty at the university for at least 2 years. Subjects were compensated with gift certificates to a local coffee shop.

2.1.2. Stimuli

Stimuli consisted of a circle with eight equally spaced dots around its perimeter presented on a computer screen. On each trial, in the center of the circle, either the word "building" or "office" was presented indicating the environment from which the target was selected. Targets were presented by replacing one dot with the name of a target. Six targets were selected for each of the environments probed (building and office). The building targets were selected a priori and included the library, patio, stairs, elevators, planter bed, and workshop. The office targets were selected by the individual subjects. Typical office targets included desks, file cabinets, computers, printers, phones, chairs, tables, pictures, windows, blackboards, doors, and bookshelves. For each environment probed, only one target was selected to occupy any given position. No targets were presented in the uppermost dot (representing the space directly in front of the subject in the imagined environment). This was done so that subjects would not become confused with respect to their heading. Thus, each target could be presented in seven different locations.

Subjects viewed the stimuli at a normal viewing distance from a computer screen (approximately 50 cm). The total display subtended 38.1 cm (approximately 37 degrees of visual angle) horizontally, and 27.9 cm (29 degrees) vertically. The circle subtended 11.5 cm (13 degrees). Each dot subtended 1.0 cm (1 degree). The display background was light gray, the circle, dots, and targets were black, and the cues were red.

2.1.3. Apparatus

The stimuli were presented at a refresh rate of 60 Hz on a Gateway VX900 monitor. A Gateway E-4200 microcomputer controlled stimulus presentation and recorded responses. Subjects made their responses on a keypad interfaced with the computer. Subjects were tested in a dimly lit room in order to minimize distraction.

2.1.4. Design

To produce an equal number of true and false placements, 12 trials were required to

counterbalance each target with respect to position and response type: each target was presented in the correct position six times and once in each incorrect position (of which there were six). Each counterbalance (12 trials/target) was crossed with the number of targets (12: 6 office, 6 building), CTI (2), and switch type (2), yielding 576 total trials. Trials were classified as either switch trials or no-switch trials based upon the environment probed on the preceding trial. To allow breaks and to minimize fatigue, trials were divided into 16 blocks consisting of 36 trials each and the delay between blocks was determined by the subject. Within each block, the CTI was constant. Subjects were informed of the CTI duration prior to the start of each block. For each subject, the blocks of trials were presented in a different random order. Also within each block, trial presentation was randomized; however, to avoid repetition priming, no target was probed on two successive trials. Accuracy and RT for each judgment were recorded. Subjects were told to respond as quickly but as accurately as possible.

Prior to the experimental trials, each subject completed two blocks of no-switch trials; one block only probed the office environment and one block only probed the building environment. Each block consisted of 144 trials. The order of the two practice blocks was counterbalanced across subjects. The CTI was always 0 ms and the intertrial interval was determined by the subject. The purpose of these trials was to ensure that subjects understood the task and knew the correct placements of each target (mean accuracy on these blocks exceeded 98%). These trials were considered practice and no results obtained from them were entered into the analyses.

2.1.5. Procedure

At the start of each block the circular display was presented (see Fig. 1). Subjects were asked to acquaint themselves with the imagined locations and environmental surroundings. The first trial was presented following a keypress from the subject indicating their readiness to begin. Immediately, a cue was presented in the center of the circle. If the CTI was 0 ms, the target appeared simultaneously with the cue. If the CTI was 2000 ms, the target appeared 2000 ms later. The target remained on the screen until the subject registered a response. Responses were made by pressing one of two keys labeled "yes" and "no" which the subject used to signal a target's correct or incorrect placement. Immediately upon the subject's response, the next trial began (i.e. the intertrial interval was always 0 ms). This created a stream of trials the subject could not disrupt. Breaks were provided at the end of each block (every 36 trials).

2.2. Results

Prior to data analysis, trials were excluded if the response was incorrect (3% of trials), or if RT was ± 3 standard deviations of the mean RT for correct trials, calculated on a subject-by-subject and cell-by-cell basis (2% of trials). Approximately 5% of trials were excluded from the analyses by this trimming process. Mean RTs were analyzed using a 2 (switch type: switch vs. no-switch) $\times$ 2 (CTI: 0 vs. 2000 ms) $\times$ 2 (probed environment: building vs. office) repeated measures analysis of variance. An alpha level less than or equal to 0.05 was adopted as the criterion for statistical reliability for all analyses. Table 1 summarizes RTs in Experiment 1 by each factor in the experimental design.

Table 1
Results, Experiment 1: mean RTs and standard errors (ms) by switch type, CTI, and probed environment

CTI (ms)	Switch type	
	Switch	No-switch
Building trials		
0	1292.6 (54.1)	1159.0 (52.7)
2000	983.6 (38.1)	972.3 (40.4)
Office trials		
0	1213.5 (42.5)	1118.8 (45.8)
2000	949.9 (51.8)	924.1 (48.0)

Fig. 2 illustrates mean RT broken down by CTI and switch type. A main effect of switch type was observed ($F(1, 5) = 37.5$, MSE = 1410). RTs on trials requiring a switch between environmental representations ($M = 1110.3$ ms) were reliably slower than trials that did not require this shift ($M = 1043.5$ ms). Additionally, a main effect of CTI was observed ($F(1, 5) = 34.6$, MSE = 19,742). When 0 ms separated the cue and target, RT was slower ($M = 1196.3$ ms) compared to trials when the CTI was 2000 ms ($M = 957.5$ ms). More importantly, a reliable interaction between switch type and CTI emerged ($F(1, 5) = 13.4$, MSE = 2040).

Planned comparisons exploring the nature of the interaction between switch type and CTI revealed a reliable switch cost (RT difference between switch and no-switch trials) when CTI was 0 ms ($F(1, 5) = 25.8$, MSE = 12,134); the magnitude of this cost was, on average, 114.1 ms. When CTI was 2000 ms, a marginal switch cost was also observed ($F(1, 5) = 4.96$, MSE = 1664, $P = 0.08$); however, the magnitude of this cost was, on average, 18.6 ms. The presence of a switch cost when CTI was 2000 ms is consistent with other task-set switching research that has shown that switch costs often do not completely dissipate, regardless of the temporal separation between tasks (e.g. Allport et al., 1994;
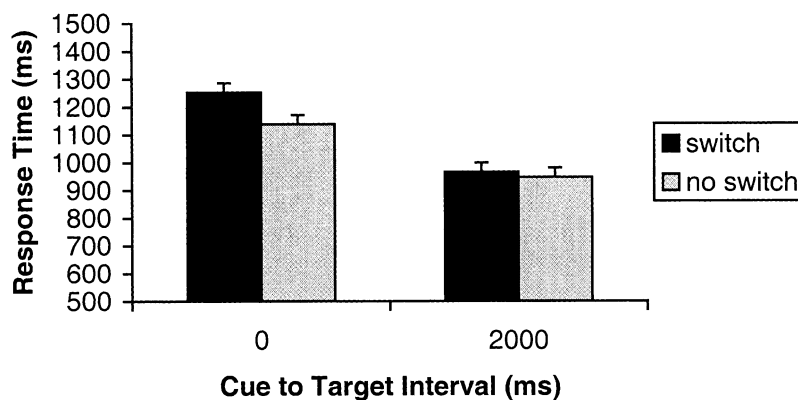

Fig. 2. The results of Experiment 1. Mean reaction times (and standard errors) are illustrated by the CTI and switch type.

Rogers & Monsell, 1995). The critical result is the interaction between switch costs and CTI as this indicates that increases in CTI provide useful time for subjects to make a switch in the probed environment.

The main effect of probed environment was reliable ($F(1, 5) = 11.8$, MSE = 2569), indicating that RT on building trials ($M = 1102.0$ ms) was slower than on office trials ($M = 1051.8$ ms). This effect may be due to the smaller scale of the office environment, or perhaps a difference in familiarity between the office and building environments. However, no interactions between the probed environment and any other factor were observed. Importantly, no reliable differences in switch costs were observed for building-to-office switches and office-to-building switches (see Table 1).

2.3. Discussion

The results of Experiment 1 suggest that the familiar building and office environments could not be retrieved/processed at the same time, despite years of navigation within them. Additional time was required by subjects to judge spatial relationships immediately following a switch in the probed environment. The cost of this shift was greater when the cue and target were presented simultaneously than when the cue was presented 2000 ms prior to the target, suggesting that switching could occur before target presentation once participants became aware of which environment the next trial would probe. In addition, switch costs did not differ with respect to the direction of the switch as equivalent costs were observed for building-to-office and office-to-building switches when the difference between environments was controlled. This result is inconsistent with the idea that the connections between representations are uni-directional in the sense that retrieving a particular representation facilitates neither the access of "superordinate" nor "subordinate" representations.

Experiment 1 does not conclusively rule out the possibility that different mental representations were maintained simultaneously for the building and office environments, however, for several reasons. First, a potential strategy, or procedural, effect could have caused the switch cost. Subjects may not have retrieved/processed environmental representations, but rather memorized correct locations of targets in the display. Because targets were presented in two individual practice sessions, one for each environment, they might have been grouped into two representations as a consequence of experience during practice. Thus, the switch cost might be an artifact of the experimental procedure, rather than reflecting the nature of environmental representations. Second, because targets belonged to two semantic categories, the switch costs could have arisen from accessing unique category information (i.e. "building things" and "office things") of the targets themselves, rather than from accessing the spatial representations of the environments. Finally, because the subjects changed the imagined location between the center of their office and the center of the building, the switch cost might be a result of this imagined movement, or spatial updating, rather than switching between environmental representations per se. In all these cases, faster RTs for no-switch trials could be observed even if both environmental representations could be simultaneously accessed. These possibilities were examined in Experiments 2 and 3.

3. Experiment 2

Experiment 2 tested the alternative hypotheses that the switch cost in Experiment 1 was an artifact of the experimental procedure or due to switching between semantic categories. Procedurally, Experiment 2 replicated Experiment 1. However, in Experiment 2, subjects were unaware that the spatial arrangement of targets represented the layout of real environments. Rather, under the premise that they were to participate in a visual memory task, subjects were told they would learn the identities of two sets of items which contained "things that may be found in a building" and "things that may be found in a personal office" and the position of each item within a visual display. These items were the same targets as those used in Experiment 1. From the subjects' point of view, each target was randomly assigned a position within the circular display that needed to be learned and remembered. Following learning, subjects were tested using the Experiment 1 procedure.

Performance in Experiment 2 was subject to the same semantic differences between the groups of targets as Experiment 1 was. However, Experiment 2 did not probe subjects' memory for layouts of real environments. Thus, if the switch costs observed in Experiment 1 were primarily due to switching between semantic categories in the absence of environmental processing, or semantic priming on no-switch trials, a similar pattern of switch costs should be observed in Experiment 2. Moreover, a longer learning and practice session was used in Experiment 2 than in Experiment 1. Thus, if the switch cost was due to grouping effects during the practice session, the effect should remain at least as strong in Experiment 2 as in Experiment 1. If, on the other hand, switch costs in Experiment 1 were due, at least in part, to switching between separate environmental representations in memory, switch costs in Experiment 2 should be greatly reduced as this component of the cost was eliminated.

3.1. Method

3.1.1. Subjects

Six members of the University of Illinois research community (mean age of 32 years) participated after providing informed consent. Subjects included faculty members, postdoctoral fellows, and upper-level graduate students. Subjects were compensated with gift certificates to a local coffee shop. None of the subjects participated in Experiment 1.

3.1.2. Stimuli

Stimuli were the same as in Experiment 1.

3.1.3. Apparatus

The same apparatus was used as in Experiment 1.

3.1.4. Design

The design was the same as in Experiment 1 with the following additions. Each subject in Experiment 2 was matched to a subject in Experiment 1 in the sense that the same office targets were used by the subject pair. The subjects in Experiment 2, however, were unaware of the source of the building and office targets and did not know that they

represented real-world spatial arrangements. Thus, before the experimental trials could begin, subjects had to learn the correct placements of targets in the circular display. During the learning period, subjects were told that they would later be tested on their memory for correct target positions. To ensure subjects did not recognize the layout of the psychology building, building targets were randomly assigned a correct location within the circular display. The correct placements of office targets directly corresponded to those in Experiment 1.

Subjects learned the positions of office and building targets in separate blocks. During the learning procedure, subjects were shown the circular display. In a string of trials, one dot on the display turned red for 1000 ms and was then replaced by the name of a target. Targets appeared in random order but were always presented in the "correct" location. Targets remained on the screen until subjects pressed a key. Immediately upon this keypress, the target name was replaced with a black dot and another dot turned red, and was replaced by the next target. Subjects were encouraged to anticipate the target that would appear at the location that turned red. In this way they could "self check" the progress of their learning. Subjects were required to view each target ten times (60 total presentations). Then, they were asked if they were ready for the memory test. If they replied no, they were given three more presentations of each target (18 total) and again asked if they were ready for the memory test. This pattern repeated until they indicated that they were prepared for the memory test. All six subjects completed the required ten presentations and one additional round of three presentations (78 presentations in all).

Following the learning procedure, subjects completed separate blocks of no-switch practice trials, as in Experiment 1. The purpose of these trials was to ensure that subjects had learned the correct placements of each target. Subjects were required to demonstrate accuracy in excess of 90% for each set of targets before proceeding to the experimental trials. All subjects exceeded this criterion in their first practice block for each target set (mean accuracy on these blocks exceeded 96%). No data from these trials were entered into the analyses.

3.1.5. Procedure
Experimental trials were conducted in the same manner as in Experiment 1.

3.2. Results

As in Experiment 1, trials were excluded if the response was incorrect (3% of trials), or if RT was ± 3 standard deviations of the mean RT for correct trials (3% of trials). Approximately 6% of trials were excluded from the analyses by this trimming process. Mean RTs were analyzed using a 2 (switch type) $\times$ 2 (CTI) $\times$ 2 (probed environment) repeated measures analysis of variance. Table 2 summarizes RTs in Experiment 2 by each factor in the experimental design.

Fig. 3 illustrates mean RT broken down by CTI and switch type. Only a reliable main effect of CTI was observed ($F(1, 5) = 17.4$, MSE = 7946). When 0 ms separated the cue and target, RT was slower ($M = 950.8$ ms) compared to trials when the CTI was 2000 ms ($M = 843.5$ ms). No other main effects were reliable. Switch trials ($M = 908.0$ ms) did not reliably differ from no-switch trials ($M = 886.3$ ms). Likewise, building trials ($M = 892.3$

Table 2
Results, Experiment 2: mean RTs and standard errors (ms) by switch type, CTI, and probed environment

CTI (ms)	Switch type	
	Switch	No-switch
Building trials		
0	973.3 (74.2)	919.3 (64.8)
2000	851.0 (59.6)	826.3 (47.4)
Office trials		
0	964.8 (81.0)	946.1 (93.7)
2000	842.9 (64.0)	853.5 (70.6)

ms) did not reliably differ from office trials ($M = 902.0$ ms). Additionally, no interactions among factors were reliable indicating that no switch costs were observed within either CTI or switch direction.

In addition to these results, a mixed model analysis of variance, using experiment as a between subjects factor, further demonstrated that RT patterns differed in Experiments 1 and 2 ($F(1, 10) = 5.21$, MSE $= 148,493$). Specifically, the effect of switch type differed in the two experiments ($F(1, 10) = 7.05$, MSE $= 1695$). In Experiment 1, when the probed environment switched across trials RT incurred a cost; this was not the case in Experiment 2.

3.3. Discussion

The results of Experiment 2 suggest that semantic differences between the two sets of targets cannot explain the pattern of results found in Experiment 1. Thus, the costs associated with switching between probed environments in Experiment 1 cannot be attributed to sequential access of semantic category information or semantic priming. The cost was also not an artifact of the experimental procedure, because it was almost eliminated in
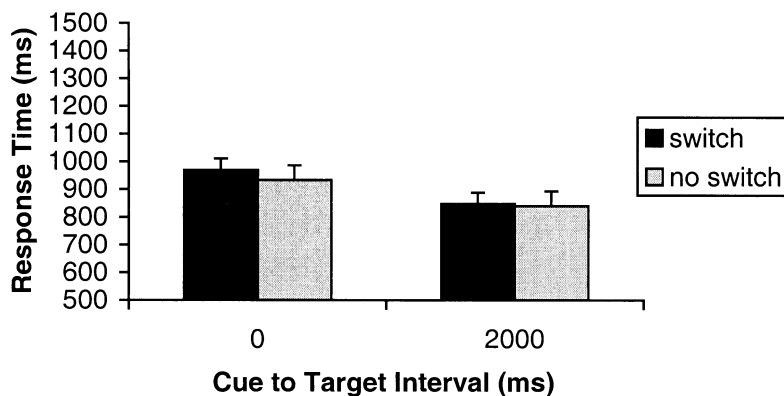
Fig. 3. The results of Experiment 2. Mean reaction times (and standard errors) are illustrated by CTI and switch type.

Experiment 2, where the total experience with individual target sets was longer (because of the added learning procedure).

There is, however, one final potential explanation for the switch costs in Experiment 1 aside from the sequential access of information from different environmental representations. In Experiment 1, even though geographical orientation was controlled, subjects nevertheless had to imagine themselves in two distinct locations (i.e. the center of their office and the center of the psychology building). Given this circumstance, it is possible that both environments were represented in either the same representation or in two simultaneously active representations and the change in imagined location by mentally "moving" from one location to the other required time, leading to a cost in RT (e.g. see Black, Turner, & Bower, 1979; Easton & Scholl, 1995). This possibility was examined in Experiment 3, where the need to "mentally translate" oneself was eliminated.

4. Experiment 3

Experiment 3 was a direct replication of Experiment 1, except that subjects always imagined being in the center of the psychology building. This eliminated the potentially time consuming need to mentally translate oneself from one point in space to another, as was required when subjects switched their imagined location between their office and the atrium of the psychology building. In Experiment 3, the probed environments were the psychology building and the surrounding university campus. Campus targets were primarily chosen for their salience. As much as possible, targets were also chosen so that they would be approximately the same Euclidean distance from the psychology building. Campus targets included a major classroom building, the student union, performing arts centers, and athletic facilities. The building targets were the same as in Experiment 1.

Predictions follow directly from Experiment 1. If the environments entail separate representations that can be accessed only one-at-a-time, RTs should incur a cost when subjects switch between building and campus judgments, and this cost should vary as a function of the CTI. On the other hand, if mental translation, or spatial updating, accounts for the results of Experiment 1, the cost in RT should be greatly diminished or eliminated when a switch in the probed environment takes place.

4.1. Method

Save for the change in probed environments, Experiment 3 was an exact replication of Experiment 1. The same subjects participated in both experiments; on average 79 days (SD = 38) elapsed between Experiments 1 and 3. Subjects were compensated with gift certificates to a local coffee shop. The same stimuli (although campus targets replaced office targets), apparatus, design, and procedure were used as in Experiment 1. Mean accuracy on the practice blocks exceeded 98%.

4.2. Results

As in Experiments 1 and 2, trials were excluded if the response was incorrect (2% of trials), or if RT was ±3 standard deviations of the mean RT for correct trials (2% of trials).

Table 3
Results, Experiment 3: mean RTs and standard errors (ms) by switch type, CTI, and probed environment

CTI (ms)	Switch type	
	Switch	No-switch
Building trials		
0	1216.3 (121.6)	1127.5 (92.5)
2000	950.5 (101.1)	916.7 (72.6)
Campus trials		
0	1255.3 (143.0)	1134.8 (104.6)
2000	962.3 (82.0)	959.4 (98.3)

Approximately 4% of trials were excluded from the analyses by this trimming process. Table 3 summarizes RTs in Experiment 3 by each factor in the experimental design.

Overall, the results of Experiment 3 replicated those of Experiment 1. Indeed, between experiments comparisons showed no reliable differences between Experiments 1 and 3. Within experiment 3, mean RTs were analyzed using a 2 (switch type) $\times$ 2 (CTI) $\times$ 2 (probed environment) repeated measures analysis of variance.

Fig. 4 illustrates mean RT broken down by CTI and switch type. A main effect of switch type was observed ($F(1, 5) = 9.22$, MSE = 4916). RTs on trials requiring a switch between environmental representations ($M = 1095.8$ ms; cf. 1110.3 ms in Experiment 1) were reliably slower than trials that did not require this shift ($M = 1034.8$ ms; cf. 1043.5 ms in Experiment 1). Additionally, a main effect of CTI was observed ($F(1, 5) = 46.1$, MSE = 14,532). When 0 ms separated the cue and target, RT was slower ($M = 1183.5$ ms; cf. 1196.3 ms in Experiment 1) compared to trials when the CTI was 2000 ms ($M = 947.0$ ms; cf. 957.5 ms in Experiment 1). Critically, a reliable interaction between switch type and CTI emerged ($F(1, 5) = 6.63$, MSE = 3369).

Planned comparisons exploring the nature of the interaction between switch type and CTI revealed a reliable switch cost when CTI was 0 ms ($F(1, 5) = 8.19$, MSE = 32,084);
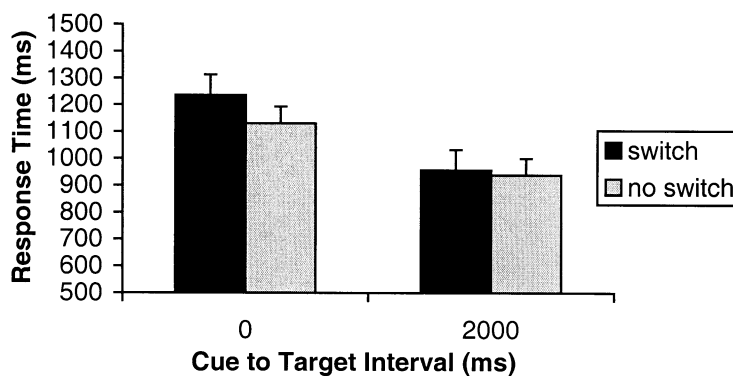

Fig. 4. The results of Experiment 3. Mean reaction times (and standard errors) are illustrated by CTI and switch type.

the magnitude of this cost was, on average, 104.6 ms (cf. 114.1 ms in Experiment 1). When CTI was 2000 ms, a switch cost was also observed ($F(1,5) = 7.66$, MSE = 1055); however, the magnitude of this cost was, on average, 18.4 ms (cf. 18.6 ms in Experiment 1). Thus, increases in CTI provided useful time for subjects to prepare for a switch in the probed environment.

The main effect of probed environment was not reliable ($F(1,5) < 1$), indicating that RT on building trials ($M = 1052.8$ ms; cf. 1102.0 ms in Experiment 1) did not differ from that on campus trials ($M = 1077.8$ ms). Thus, the switch cost cannot be explained by baseline differences in RT to each environment. In addition, no interactions involving probed environment were observed. Importantly, no reliable differences in switch costs were found between campus-to-building switches and building-to-campus switches (see Table 3).

Before closing the results section, we note that although the repetition of subjects in Experiments 1 and 3 allowed for a within-subjects analysis of whether controlling the imagined reference position affects switch costs, a potential problem is that subjects completed Experiment 1 prior to Experiment 3. This previous experience could have biased subjects to respond as they did in Experiment 1, thereby leading to similar results in the two experiments. To rule out this account of the data, Experiment 3 was repeated using a new set of naive subjects that had not participated in Experiments 1 or 2. The results of this replication followed those of Experiment 3 (and Experiment 1) very closely and are illustrated in Fig. 5. Switch trials (996.9 ms) were slower than no-switch trials (940.3 ms) ($F(1,5) = 5.40$, MSE = 7121), and 0 CTI trials (1030.6 ms) were slower than 2000 CTI trials (906.7 ms) ($F(1,5) = 11.9$, MSE = 15,496). A reliable interaction between switch and CTI was observed where switch trials were 111.5 ms slower than no-switch trials when CTI was 0 ms compared to 1.7 ms when CTI was 2000 ms ($F(1,5) = 11.7$, MSE = 3098). Finally, no differences were observed between building (969.7 ms) and campus trials (967.6 ms) ($F(1,5) < 1$), and probed environment did not interact with switching environment ($F(1,5) = 2.9$). These results indicate that those of Experiment 3 were not due to a response bias introduced to subjects by completing Experiment 1 first.
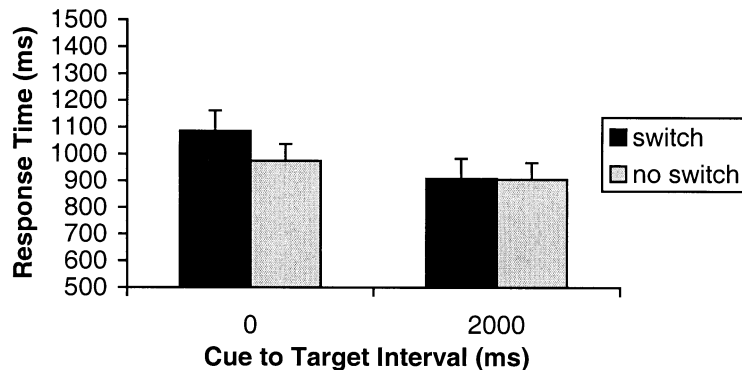

Fig. 5. The results of Experiment 3, replicated with new subjects. Mean reaction times (and standard errors) are illustrated by CTI and switch type.

4.3. Discussion

The results of Experiment 3 directly replicated those of Experiment 1. Additional time was required by subjects to judge spatial relationships following a switch in the probed environment. Furthermore, the cost of this shift was greater when the cue and target were presented simultaneously than when the cue was presented 2000 ms prior to the target. This indicates that while making judgments concerning a particular environment, subjects were not prepared to address other environments. Rather, some time was required for subjects to mentally switch representations. In addition, RT costs did not differ with respect to the direction of the switch as equivalent costs were observed for building-to-campus and campus-to-building switches. This result again suggests that if these environments are part of a hierarchical framework, access of "lower level" representations does not necessarily imply access of "higher level" representations, or vice versa.

Note that in this experiment subjects imagined themselves at the same location and orientation in the two environments, thus eliminating the need to mentally translate themselves between locations in space. In other words, because the spatial relationship between targets in both environments and the subjects remained constant throughout the experiment, no spatial updating was needed. Thus, the switch costs observed in Experiment 3 were not due to factors related to changing perspective, or updating, but indeed due to access of two environmental representations that cannot be held active simultaneously.

Finally, we note that although Experiment 3 showed that the switch cost was not a result of imagined self-translation, it does not suggest that switching perspectives, or spatial updating, is cost-free. Previous research on spatial reasoning has convincingly demonstrated that changing perspectives takes time (e.g. Easton & Scholl, 1995; Farrell & Robertson, 1998; Huttenlocher & Presson, 1979; Presson, 1982; Rieser, 1989; Shelton & McNamara, 1997). Although outside the scope of this paper, in light of these observations, the role perspective change may have in switching between two environments may be an interesting topic of future investigation.

5. General discussion

Research over the past 20 years has suggested that humans store multiple spatial representations of the environment, each of which encodes information about some local aspects of the world. However, few theories or models of environmental representations have explicitly examined how environmental representations are accessed, or made predictions about the access process. The present experiments specifically investigated how representations of familiar environments are accessed, and whether one can access spatial knowledge of different environments simultaneously as if one can mentally "see" them as a whole, or if the representations must be accessed sequentially as if one can only consider a single environment at a time.

Three experiments were consistent with the hypothesis that environmental representations are accessed sequentially. Judgments of the spatial relationships among targets within a given environment were slower when the previous trial involved a different environment than when it involved the same environment, as if the participants had to

take time to switch mental representations of one environment to another. This switch cost was not a result of switching between two semantic categories or spatial updating of the imagined target locations. This suggests that spatial knowledge of different environments cannot be accessed simultaneously, even if the environments are highly familiar and closely related to each other through repeated, daily navigation.

What is the nature of the knowledge that must be switched with each new environment? One possibility is that different environments may be encoded in different spatial reference frames, and accessing an environmental representation requires activating the corresponding reference frame. This hypothesis is supported by findings that switching between reference frames takes time (e.g. Carlson-Radvansky & Jiang, 1998). However, notions of what and how information is encoded in environmental representations vary widely depending on the paradigm in which they are studied. It has been proposed that the representations themselves may contain spatial (Stevens & Coupe, 1978), and nonspatial (Hirtle & Jonides, 1985) information. Additionally, it is unclear whether they are allocentric (Tolman, 1948), egocentric (e.g. Wang, 1999; Wang & Spelke, 2000), perspective-dependent (Diwadkar & McNamara, 1997), or perspective-free (Taylor & Tversky, 1992b). Thus, future experimental work needs to address which aspects of environmental representations, and under what conditions they are accessed, lie at the core of the switch cost as different representations are retrieved from memory.

Unlike previous studies which focused on the *structure* of the representational system (see the discussion of hierarchies presented in Section 1), the current experiments focused on the *processing* of those representations. Although the current experiments do validate the notion of multiple, independent representations, they do not allow strong claims about the structure of the representational system. For example, the current experiments do not definitively validate or challenge hierarchical theories. However, given the dominance of hierarchical theories in the current environmental literature, we consider some implications of our results on such theories and their collective impact on conceptions of spatial processing, including representational networks, spatial reasoning, bias effects in spatial judgments, directionality of processing, effects of familiarity, viewpoint dependence, and navigation.

Although results of these experiments were inconsistent with the claim that information from multiple representations can be retrieved simultaneously, they do not rule out the possibility that partial activation can occur in several representations. For example, McNamara (1986) proposed that spatial judgments are produced by a network of activation across nodes (see Anderson, 1983 for detailed discussion of network models), which denote specific pieces of spatial knowledge and are organized in several levels representing the different tiers of an overall hierarchy. When a node is accessed, it radiates activation to adjacent nodes, both at the same and at different levels. Thus, when one node is accessed in order to make some kind of spatial judgment, a series of nodes at different hierarchical levels become active as well. However, such activation does not allow the relevant spatial information to be readily used for the judgment task (i.e. be "accessible"), much like a light bulb can conduct current without being illuminated. Thus, the switch costs observed in our experiments could very well have arisen even if some residual activation was present in the representation of the environment that was not probed. Nevertheless, our results show that some additional cognitive effort (e.g. a process that

further activates specific representations) is involved when a change of environment occurs.

Animals must either switch the active environmental representation or consider information from multiple representations to complete various tasks. For example, when one must judge spatial relationships among targets encoded in separate representations or, during navigation, when one travels from one room in a building to another, the active environmental representations that provide the appropriate information must be switched. Thus, the result that only one representation can be accessed at a time has important implications on models of spatial reasoning.

Although it is clear that spatial knowledge is often computed from information stored in several different representations (Huttenlocher et al., 1991; McNamara, 1986; Stevens & Coupe, 1978), it is not known how spatial information from different representations is combined. Some computational models designed to explain bias effects produced when spatial judgments span multiple representations (e.g. Huttenlocher et al., 1991; see also McNamara, 1986) have implicitly assumed that representations are simultaneously accessed, a hypothesis contradicted by the current results. Under simultaneous access accounts, bias could simply be the summary product of the concurrent access and activation of two or more representations. Thus, most models focused on *what* representations are accessed, and tended to ignore the question of *how* these representations are accessed. In a serial access account where people continually change the active representation during spatial processing, however, information must be extracted from each representation in some order. Spatial judgments, then, result from a process which then systematically computes a solution from input extracted over time. How many representations can be "juggled" in this sense without losing computational accuracy remains an interesting question.

The serial nature of accessing spatial representations raised an important question. Given the constraint of serial access, bias effects – and more generally, spatial judgments – reflect the presence of some cognitive function that occurs after information for the relevant representations has been retrieved. When considering environmental surroundings, however, it is unlikely that information is accessed haphazardly in the hope of retrieving the appropriate data necessary for the task at hand, whether it be simple direction computation or complex navigation. Where do people begin, and in what order do they proceed?

The idea that representations are organized in a hierarchical structure may be important to this issue. Particularly, does access of spatial information follow certain directions in the hierarchy, such as top-down or bottom-up? In the present experiments neither representation was asymmetrically influenced by previous consideration of the other environment. Thus, it appears that a single representation is accessed rather independently of other representations and does not automatically include access of other representations, for instance, at adjacent levels of the hierarchy. This conclusion does not, however, exclude the possibility that when information from multiple representations, even if they occupy distinct levels of a hierarchy, must be retrieved, access follows an orderly sequence. For example, the preliminary access of global (superordinate) information may provide a useful representational framework within which later retrieved local (subordinate) information can be integrated. That is, when considering objects housed in various regions of a

room (e.g. McNamara, 1986) initial access of the more abstract "room representation" can provide a useful context when accessing specific information from the individual "region representations". Moreover, because subordinate information is interpreted within the framework established by the superordinate information, it is not surprising that top-down biases may sometimes result. Evidence for such global-to-local processing has been suggested in several perceptual and cognitive tasks (e.g. Navon, 1977; Palmer, 1980; Pomerantz, Sager, & Stover, 1977; Sanocki, 2001; Weisstein & Harris, 1974).

Finally, it has been unclear from past research if familiarity with a real-world environment may allow free access of environmental knowledge. Our subjects have spent years navigating through the university campus, the psychology building, and their respective offices. It was reasonable to hypothesize that if initially local representations can gradually become fused, such integration would have occurred in our subjects. Although we have no baseline for comparison (we do not know how the representations were encoded when our subjects were still novices with respect to these environments), it is clear that neither the campus, building, nor office were completely fused into a single representation because subjects were apparently not able to "visualize" both environments at the same time. This result suggests that expertise and familiarity with an environment may not enable once separable representations to become completely integrated.

How then, do humans and animals become progressively more able to compute spatial relationships across different environments and unexperienced viewpoints? One account consistent with the retention of multiple representations tied together in a hierarchical network seems possible. Namely, when an animal is faced with a novel environment or is restricted in its exploration of that space, the locations are initially encoded as separate, viewpoint-dependent environments. Once experience with the environment increases or as navigation becomes unrestricted, the animal then establishes the "connections" between representations, which nonetheless remain separable. The resulting network can then function like the framework suggested by McNamara (1986) and thereby enable better behavioral performance.

In short, the present experiments are consistent with many of the claims made by hierarchical models of environmental representations using a spatial judgment task in highly familiar environments. However, they also indicate that the processing of mental representations of environments is more complex than past research suggests, and future research on, and conceptions of, environmental representations need to account for how spatial judgments are made in greater detail.

Acknowledgements

References

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and performance* (pp. 421–452), Vol. XV. Cambridge, MA: MIT Press.

Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard University Press.

Baird, J. C., Merrill, A. A., & Tannenbaum, J. (1979). Studies of the cognitive representation of spatial relations: II. A familiar environment. *Journal of Experimental Psychology: General*, *108*, 92–98.

Baum, D. R., & Jonides, J. (1979). Cognitive maps: analysis of comparative judgments of distance. *Memory & Cognition*, *7*, 462–468.

Biederman, I. (1973). Mental set and mental arithmetic. *Memory & Cognition*, *1*, 383–386.

Black, J., Turner, T., & Bower, G. (1979). Point of view in narrative comprehension, memory, and production. *Journal of Verbal Learning and Verbal Behavior*, *18*, 187–198.

Carlson-Radvansky, L. A., & Jiang, Y. (1998). Inhibition accompanies reference frame selection. *Psychological Science*, *9*, 386–391.

Diwadkar, V. A., & McNamara, T. P. (1997). Viewpoint dependence in scene recognition. *Psychological Science*, *8*, 302–307.

Easton, R. D., & Scholl, M. J. (1995). Object-array structure frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 483–500.

Ellen, P., Parko, E. M., Wages, C., Doherty, D., & Herrmann, T. (1982). Spatial problem solving by rats: exploration and cognitive maps. *Learning and Motivation*, *13*, 81–94.

Ellen, P., Soteres, B. J., & Wages, C. (1984). Problem solving in the rat: piecemeal acquisition of cognitive maps. *Animal Learning & Behavior*, *12*, 232–237.

Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and the automatic updating of body centered spatial relationships. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 227–233.

Hirtle, S. C., & Jonides, J. (1985). Evidence of hierarchies in cognitive maps. *Memory & Cognition*, *13*, 208–217.

Huttenlocher, J., Hedges, L. V., & Duncan, S. (1991). Categories and particulars: prototype effects in estimating spatial location. *Psychological Review*, *98*, 352–376.

Huttenlocher, J., & Presson, C. C. (1979). The coding and transformation of spatial information. *Cognitive Psychology*, *11*, 375–394.

Jersild, A. T. (1927). Mental set and shift. *Archives of Psychology*, Whole No. 89.

Levine, M., Jankovic, I. N., & Palij, M. (1982). Principles of spatial problem solving. *Journal of Experimental Psychology: General*, *111*, 157–175.

Mazmanian, D. S., & Roberts, W. A. (1983). Spatial memory in rats under restricted viewing conditions. *Learning and Motivation*, *14*, 123–139.

McNamara, T. P. (1986). Mental representations of spatial judgments. *Cognitive Psychology*, *18*, 87–121.

McNamara, T. P., Hardy, J. K., & Hirtle, S. C. (1989). Subjective hierarchies in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 211–227.

Navon, D. (1977). Forest before trees: the precedence of global features in visual perception. *Cognitive Psychology*, *9*, 353–383.

Palmer, S. E. (1980). What makes triangles point: local and global effects in configurations of ambiguous triangles. *Cognitive Psychology*, *12*, 285–305.

Pomerantz, J. R., Sager, L. C., & Stover, R. J. (1977). Perception of wholes and of their component parts: some configural superiority effects. *Journal of Experimental Psychology: Human Perception and Performance*, *3*, 422–435.

Poucet, B. (1993). Spatial cognitive maps in animals: new hypotheses on their structure and neural mechanisms. *Psychological Review*, *100*, 163–182.

Presson, C.C. (1982). Strategies in spatial reasoning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *8*, 243–251.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*, 1157–1165.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231.

Sanocki, T. (2001). Interaction of scale and time during object identification. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 290–302.

Shelton, A. L., & McNamara, T. P. (1997). Multiple views of spatial memory. *Psychonomic Bulletin & Review*, *4*, 102–106.

Spector, A., & Biederman, I. (1976). Mental set and mental shift revisited. *American Journal of Psychology*, *89*, 669–679.

Stevens, A., & Coupe, P. (1978). Distortions in judged spatial relations. *Cognitive Psychology*, *10*, 422–437.

Sudevan, P., & Taylor, D. A. (1987). The cuing and priming of cognitive operations. *Journal of Experimental Psychology: Human Perception and Performance*, *13*, 89–103.

Sutherland, R. J., Chew, G. L., Baker, J. C., & Linggard, R. C. (1987). Some limitations on the use of distal cues in place navigation by rats. *Psychobiology*, *15*, 48–57.

Taylor, H. A., & Tversky, B. (1992). Descriptions and depictions of environments. *Memory & Cognition*, *20*, 483–496.

Taylor, H. A., & Tversky, B. (1992). Spatial mental models derived from survey and route descriptions. *Journal of Memory and Language*, *31*, 261–292.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, *55*, 189–208.

Wang, R. F. (1999). Representing a stable environment by egocentric updating and invariant representations. *Spatial Cognition and Computation*, *1*, 431–455.

Wang, R. F., & Spelke, E. S. (2000). Updating egocentric representations in human navigation. *Cognition*, *77*, 215–250.

Weisstein, N., & Harris, C. S. (1974). Visual detection of line segments: an object superiority effect. *Science*, *186*, 752–755.

Wilton, R. N. (1979). Knowledge of spatial relations: the specification of information used in inferences. *Quarterly Journal of Experimental Psychology*, *31*, 133–146.