Journal of Experimental Psychology:
Learning, Memory, and Cognition
2006, Vol. 32, No. 3, 506–515

Copyright 2006 by the American Psychological Association
0278-7393/06/$12.00 DOI: 10.1037/0278-7393.32.3.506

Individual Skill Differences and Large-Scale Environmental Learning

Alexa W. Fields and Amy L. Shelton
Johns Hopkins University

Spatial skills are known to vary widely among normal individuals. This project was designed to address whether these individual differences are differentially related to large-scale environmental learning from route (ground-level) and survey (aerial) perspectives. Participants learned two virtual environments (route and survey) with limited exposure and tested on judgments about relative locations of objects. They also performed a series of spatial and nonspatial component skill tests. With limited learning, performance after route encoding was worse than performance after survey encoding. Furthermore, performance after route and survey encoding appeared to be preferentially linked to perspective and object-based transformations, respectively. Together, the results provide clues to how different skills might be engaged by different individuals for the same goal of learning a large-scale environment.

Keywords: spatial memory, environmental learning, individual differences

Successful navigation in large-scale environments is vital to survival; humans need to be able to consistently find their way to shelter and resources. However, little is understood about why different individuals seem to have different comfort levels with the various styles of environmental learning. This project was designed to help elucidate how environmental learning might differ among individuals and how the learning process might be made more efficient.

Two of the primary methods of real-world environmental learning used by humans are exploratory navigation and map reading. Exploratory navigation, a type of wayfinding behavior (Allen, 1999), involves moving through a space to establish the layout of the environment and the relative locations of objects within the environment, whereas map reading (usually) involves reading a stationary, abstracted representation of the space from a more global perspective. Both of these methods appear to be equally effective for many tasks of environmental learning (e.g., Denis, Pazzaglia, Cornoldi, & Bertolo, 1999; Passini, 1984). However, research has demonstrated that these different types of learning lead to differences in the spatial information one retains about the environment (Thorndyke & Hayes-Roth, 1982; Moeser, 1988), suggesting that different skills may be called upon by each method.

One approach to systematically studying the differences between learning via exploratory navigation and map reading has been to simplify the problem by examining the two different spatial perspectives from which exploratory navigation and map reading take place: a first-person, ground-level perspective ("route encoding"), and an aerial, map-like perspective ("survey encoding") (Shelton & McNamara, 2004; Shelton & Gabrieli, 2002, 2004).[1] Distinctions between route and survey encoding have primarily been made in the neuroimaging literature. Route encoding preferentially activates areas associated with integration and updating of egocentric orientations, whereas survey encoding preferentially activates more object-processing areas (Shelton & Gabrieli, 2002, 2004). Similar patterns also have been observed in brain activation during retrieval (Mellet et al., 2000). However, attempts to make a distinction between route and survey encoding in terms of behavioral performance have been less successful. For example, Shelton and McNamara (2004) had participants learn virtual environments from route and survey perspectives, and then tested them on scene recognition, using still images of the environment from a route perspective and from a survey perspective. Participants were required to discriminate between images that either correctly or incorrectly represented the environment viewed. Recognition performance was best when the test perspective (i.e., the perspective of the still image) matched encoding perspective. However, overall performance did not differ after route and survey encoding. Performance after route and survey encoding also did not differ when participants performed judgments of relative direction (JRDs). In this task, participants were required to estimate the relative angle from an imagined heading defined by two objects to a third target object. The JRD task is considered to be a more direct test of spatial memory than visual scene recognition (see Shelton & McNamara, 2004, for discussion).

However, these previous studies typically used seven or more complete runs through each environment during encoding. Extensive pilot work demonstrated that beyond five runs, there is no improvement in speed or accuracy of scene recognition, judgments of relative direction, or map drawing. Moreover, recent studies have shown that four to five viewings of a movie are sufficient for

Alexa W. Fields and Amy L. Shelton, Department of Psychological and Brain Sciences, Johns Hopkins University.

We thank Susan Courtney for her comments on previous versions of the manuscript. We also thank Giselle Spence and Nisha Jambulingam for their help in scoring the test battery.

Correspondence concerning this article should be addressed to Amy L. Shelton, Department of Psychological and Brain Sciences, Ames Hall/3400 North Charles Street, Johns Hopkins University, Baltimore, MD 21218. E-mail: ashelton@jhu.edu

---

[1] These two types of *information* should be distinguished from route and survey *knowledge* constructs. The former reflects how spatial information is obtained, whereas the latter reflects how that information is mentally represented. Although the two concepts may be related at some level, this study was not designed to address such a relationship.

most participants to feel that they have effectively encoded a virtual environment (Shelton, Jambulingam, & Clark, 2005). Therefore, the apparent overlearning in previous studies might have masked any differences between route and survey encoding. Using limited learning (at four runs or fewer) may reveal accuracy differences in retrieval tasks and/or for different individuals after route and survey encoding. It is likely that individual differences in spatial skills may affect which strategies participants use during encoding and retrieval, as well as how effectively the participants make use of those strategies. For example, when performing JRDs, participants may imagine themselves rotating and translating within the environment (as occurs during exploratory navigation), or they may imagine the environment as an external entity rotating as a whole (as may occur during map reading, if the map is turned). Therefore, if performance on JRDs differs for the two perspectives and among participants, it is likely that these differences will be attributable to individual differences in transformational processes and other skills.

Researchers have long known that individuals differ widely on spatial skills, including mental rotation (Just & Carpenter, 1985; Mumaw, Pellegrino, Kail, & Carter, 1984; Vandenburg & Kuse, 1978), reasoning about spatial perspectives (Hegarty & Kozhevnikov, 1999), location memory (O'Dekirk, Wyatt, & Ellis, 1993), sense of direction (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002; Sholl, 1988), and map retention (Schwartz & Philippe, 1991). Although individual differences in large-scale spatial learning/wayfinding have long been of interest to cognitive psychologists (e.g., Hirtle & Hudson, 1991; Kozlowski & Bryant, 1977; Montello & Pick, 1993; Richardson, Montello, & Hegarty, 1999; Weisman, 1981), the relationship between large-scale environmental learning and specific individual component skills has received limited attention (see Allen, 1999 for a review). Allen, Kirasic, Dobson, Long, & Beck (1996) conducted a factor analysis to examine the relationship between general spatial ability and measures of environmental learning. The results suggested that general spatial ability was not directly correlated to environmental learning, but rather mediated by two cognitive skills: spatial-sequential memory and perspective taking. To uncover a more direct link between spatial skills and environmental learning, we attempt to focus on specific key component spatial skills, rather than a general measure of visuospatial ability. In addition, we extend the issue of large-scale learning by considering different sources of spatial information.

Rather than casting a broad net on all possible spatial skills, we focused on three potentially relevant skills for which hypotheses could be clearly developed. First, mental rotation has already been established as a key component spatial skill (Pazzaglia & De Beni, 2001; Shelton & Gabrieli, 2004). For example, Pazzaglia and De Beni found that better mental rotation ability was associated with a preference for survey information, suggesting a relationship between survey-based information and mental rotation. Second, the ability to adopt different perspectives (i.e., spatial perspective taking) is another type of mental transformation that may be relevant (Kozhevnikov & Hegarty, 2001; Hegarty & Waller, 2004). Allen et al. (1996) demonstrated that perspective taking may mediate the relationship between general spatial ability and environmental learning. We hypothesize that facility with recognizing, adopting, and combining different perspectives may be related to route encoding, given that route encoding requires keeping track of a changing perspective of the environment. Adopting alternative perspectives may be less important for survey encoding, given that survey encoding occurs from a fixed perspective on the environment. Together, these first two skills reflect potential differences in the types of mental transformations one might use during environmental learning.

Finally, spatial working memory, remembering locations of objects for short durations, is a necessary component for learning environments over time. However, route and survey encoding may make different demands on this skill. During survey encoding, the global layout is more readily accessible (one can see wall edges, corners, etc.) and a single orientation is maintained. Alternatively, route encoding requires using local information to make inferences about global structure and maintaining that information over changes in perspective. Although both types of encoding require some maintenance of object location, the additional burden of inferring and maintaining a global structure during route encoding likely taxes the working memory system more than the mere rehearsal of previously seen relative locations. This may be akin to the distinction between maintenance and maintenance plus manipulation identified in the broader working memory literature (e.g., Jonides et al., 2003). Support for this hypothesis comes indirectly from neuroimaging studies in which frontal regions (commonly associated with working memory) tended to be more active for route than for survey during encoding (Shelton & Gabrieli, 2002) and retrieval (Mellet et al., 2000).

Although environmental learning is clearly classified as a spatial problem, an investigation into nonspatial skills may provide insights into how nonspatial strategies might be engaged to help solve spatial problems. For example, participants in pilot studies were apt to speak to themselves in the form of a running verbal commentary (e.g., "All right, the carousel is next to the swings, and around the corner is the slide, and now I'm back at the fountain again."). This strategy may depend on such skills as verbal working memory or language processing. As such, the present study includes a small set of nonspatial skills, including nonspatial working memory, language, and speed of processing, to determine how these skills contrast with or complement the spatial skills under investigation.

When focusing on individual differences in spatial skills, it is important to consider the extensive psychometric literature on sex differences, demonstrating that men tend to outperform women on certain types of spatial ability tests, especially object-based mental rotation tasks (see Montello, Lovelace, Golledge, & Self., 1999, for a review). Gender differences in map learning have also been reported, with men performing better on tests of euclidean geometric knowledge, and women recalling more landmarks than men (Galea & Kimura, 1993). However, previous studies involving room-sized or larger environments have failed to find gender differences in behavioral performance for scene recognition or JRDs (Shelton & McNamara, 1997, 2001, 2004). This dichotomy between the individual differences literature and the large-scale learning studies can be partially addressed in the present study by including gender as a variable for both investigating overall differences under more limited learning and examining whether skills that predict performance differ for men and women. Although this is not a primary focus of the study, this inclusion will provide some clues as to how to think about gender differences in spatial skills.

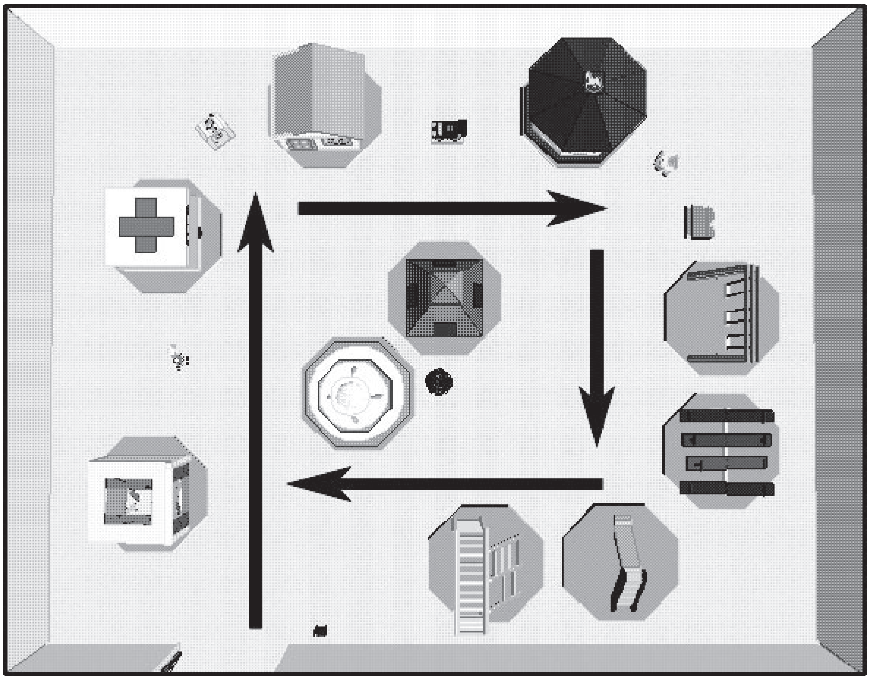


Figure 1. Aerial view of the City Park environment. The path through the environment is identified by the superimposed black arrows (arrows are not present during viewing).

Materials and Methods

Participants and Design

Forty participants (20 women) volunteered in return for extra credit in psychology courses at Johns Hopkins University. Each participant viewed one environment assigned to a particular perspective (e.g., the City Park from a route perspective), and the other environment assigned to the other perspective (e.g., the Zoo from a survey perspective). Equal numbers of men and women participants were randomly assigned to one of four conditions, counterbalancing the perspective to which a given environment was assigned (Park-Route/Zoo-Survey, or Park-Survey/Zoo-Route) and the order in which the two environments were learned (The route environment first, then the survey environment; or vice versa).

Route/Survey Movies

Two desktop virtual environments were used, a City Park and the Zoo. These were updated versions of the environments used by Shelton and McNamara (2004) and Shelton and Gabrieli (2002, 2004). Each environment measured approximately 110 ft × 130 ft (330 m × 390 m) in virtual space, and contained 10 large landmarks, 7 small landmarks, and fixed features such as walls and sidewalks. Environments were designed to be visually distinct, such that there was no overlap of landmarks across environments. Two navigation movies were recorded for each environment, one from each of the encoding perspectives. The survey movie was recorded from the perspective of an aerial observer, 70 ft (210 m) above the ground in virtual space, looking straight down. The path began at the entrance to the environment (always in the lower left corner) and proceeded in a square path around the environment, but without any changes in heading (i.e., no turns).[2] The route movie was recorded from the perspective of a 6-ft (1.8-m) tall observer walking through the environment. The path began at the entrance (as in the survey movie) and proceeded along the same path as in the survey movie, making right turns at each of the corners and ending with a left turn toward the entrance (as shown in Figure 1). Approximately 20% of the environment was visible at any given time, for each movie. Each movie lasted 46 seconds.

JRDs

The JRD test requires estimating the relative angular direction of a target landmark from an imagined heading (as defined by two other landmarks in the environment). Different combinations of the 10 large landmark objects were used to construct trials for each environment (e.g., “Imagine you are standing at the clock tower, facing the fountain. Point to the carousel.”). Because of the structural limitations of the environments, imagined headings (as defined by a combination of two objects) were binned into eight different heading categories: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. The initial path heading for route, and the fixed heading, for survey, arbitrarily defined the zero-degree heading. A given trial was classified into a heading category if it was within 15° of the category label (e.g., 45° headings ranged from 30° to 60°). To allow for counterbalancing, trials were also categorized according to the pointing direction of the target object (straight ahead = 0°): front (315° to 45°), right (45° to 135°), back

---

[2] The fixed orientation of the survey movies was intended to approximate map reading. In the real world, individuals typically read maps not by rotating the map but by holding the map upright in one preferred orientation. In other studies in our laboratory, we have used conditions that include turns (what we often consider to be “hybrid” conditions), but those were not included in this experiment. It may be useful to consider whether there are additional individual differences in preference and performance for the fixed survey compared with the survey-with-turns, but this issue is outside the scope of the present investigation.

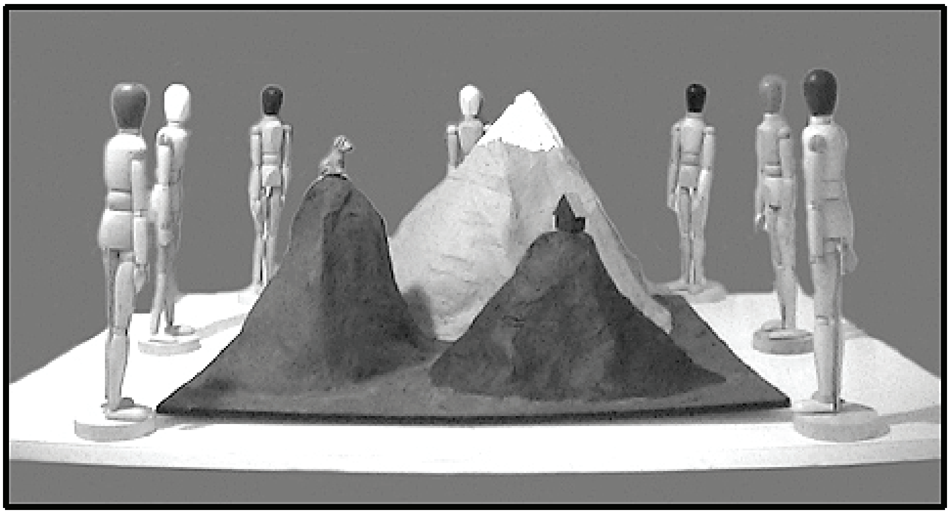


Figure 2. The Three Mountains Test layout.

(135° to 225°), and left (225° to 315°).[3] From all possible trials, 64 were selected, such that there were two trials at every combination of imagined heading and pointing direction.

Spatial Skill Tests

Three Mountains. To test perspective taking, participants were presented with a modification of Piaget's (Piaget & Inhelder, 1967) Three Mountains Test (3 Mts.), which requires participants to identify which doll sees a physical display from a particular perspective. The participants were shown the display of three mountains depicted in Figure 2 from one perspective (0°). A series of seven wooden artist's model dolls with different color heads were arranged around the display such that their perspectives represent headings of 45°, 90°, 135°, 180°, 225°, 270°, and 315° (with respect to the participants' view, designated as 0°). The participants were then shown several test views, each of which corresponded to one of the dolls' perspectives. Participants answered by pressing the color key that matched the color of the appropriate doll's head. Response time and accuracy were recorded for each trial. However, accuracy (% correct) is the primary measure of interest.

Mental Rotation Test. The Mental Rotation Test (MRT; Vandenberg & Kuse, 1978) was used to assess ability of the participants to mentally manipulate three dimensional objects. Modeled after the original Shepard and Metzler (1971) mental rotation task, this test has been demonstrated to reliably produce a wide range of individual differences. Scores on the MRT reflect cumulative number correct out of 40.

Road Map Test. The Money Road Map Test (Money & Alexander, 1966) was used to assess participants' ability to make left-right discriminations on a map. This task is intended to capture elements of map reading and spatial transformation. The score on this test reflects number correct of 32.

Spatial Perspective Test. The Spatial Perspective Test (Kozhevnikov & Hegarty, 2001) was used to test people's ability to take imagined perspectives in space. This task taps into egocentric perspective taking, which has been dissociated from object rotation in performance (Zacks, Mires, Tversky, & Hazeltine, 2000) and brain activation (Zacks, Mires, Tversky, & Hazeltine, 1999). Score on this test reflects the average absolute angular error.

Questionnaire on Spatial Representation. To assess preferences for route and survey information, participants completed the Questionnaire on Spatial Representation (Pazzaglia & De Beni, 2001), which comprises 11 items that assess general sense of direction and spatial preferences. Responses to items on the test were used to create a score that signifies whether the participant tends to prefer dealing with route-based (score <0) or survey-based (score >0) information. This test will be hereafter referred to as the Questionnaire.

Spatial Span. The spatial span task was adapted from Kail's (1991) matrix span task, in which participants are presented with a 4×4 grid with different numbers of X's in them. For this study, grids were randomly generated with sets of 4, 5, 6, 7, 8, or 9 Xs in them. From these, two grids were selected for each set length. Selection criteria for the grids were as follows: (a) No row or column of the grid could be completely filled in with X's, (b) the X's could not form a symmetrical pattern, and (c) the X's should not be tightly clustered together. All grids were presented on the computer screen, using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993), in order of increasing set length. Each matrix was presented for 5 s. Participants recalled by printing X's on blank matrices. Three different methods of scoring were tested: (a) total span, measured as the total number of correctly remembered locations; (b) absolute span, measured as the total number of locations correctly remembered only in the grids that were remembered perfectly; and (c) set span, or the highest set size at which both grids were remembered perfectly. However, because of the high intercorrelation between the three methods ($r > .83$, in each case), only the absolute span measure was used in the analysis.

Nonspatial Skills Tests

Symbol Digit Modalities Test. Speed of processing was measured using the Symbol Digit Modalities Test (Smith, 1968). Score was recorded as the total number of correct answers. This test will be hereafter referred to as Symbol Digit.

Reading Passages. Language skills were measured using the Passage Comprehension subtest of the Woodcock-Johnson III test battery (Woodcock, McGrew, & Mather, 2001). Accuracy was measured by the total number of appropriate answers that participants provided.

Digit Span. The digit span task was adapted from the task used by Kail (1991). Using PsyScope software (Cohen et al., 1993), random sequences

---

[3] This categorization was used solely for counterbalancing pointing direction. All measurements of error were made relative to the actual angle of pointing response from the actual angle of imagined heading.

of digits were presented on the computer screen at a rate of one digit per second, with no repeating digits within a sequence. At the end of each sequence, a question mark appeared on the screen, prompting participants to speak out loud the digits in order. To measure accuracy, the experimenter wrote down the digits as they were presented on the screen and checked the participant's spoken recall against the correct digits. Two digit sequences were presented at each set length, from four to eight digits. The task was halted once the participants made errors on both presentations of a given set length. Digit span was calculated as the maximum set length at which participants were able to correctly recall both of the sequences.

Word Span. The word span task used the same parameters as the digit span test, substituting words for digits. The word list, which consisted of 80 four- and five-letter words matched as closely as possible for rank of usage in the English language, was taken from La Pointe and Engle (1990).

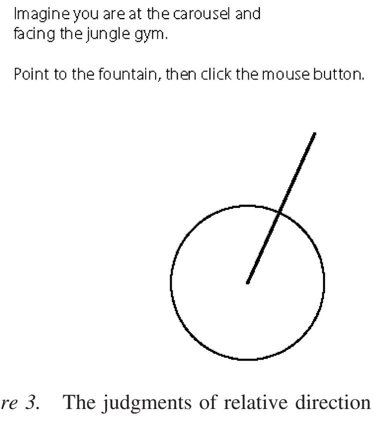
Procedure

Route/Survey Encoding

Participants were instructed to learn the environments for a later memory test. First, the experimenter guided the participants through a practice viewing of the environment, pointing out the names of the 10 large landmarks along the way. The participant was then left to watch the remaining runs of the movie. Pilot testing determined that the three total runs of the movie per environment (including the practice viewing) were insufficient for participants to successfully encode either route or survey encoding environments (JRDs were at chance). Therefore, participants were given four total runs of the environment, including the practice viewing, which is just below the average number of runs that participants chose to view when given license to self-terminate their environmental learning (Shelton, Jambulingam, & Clark, 2005).

Retrieval Task and Skill Tests

JRDs. After encoding the environment for a given perspective, participants were given JRDs for that environment, followed by a second session of encoding and JRDs for the other perspective and environment. Figure 3 shows an example of the trial format. Each trial was presented on a computer screen, along with a virtual pointer (a line placed within a circle). Using a mouse, participants positioned the pointer line to reflect where the target object would be, given the prescribed heading. The study participant entered the intended answers by clicking the mouse. Response latency and angular error were recorded for each trial. Six practice trials were conducted beforehand (using the relative positions of buildings on the Johns Hopkins campus) in order to familiarize participants with the task protocol. Participants were given a 20-min time limit to finish up to 64 trials. If they did not complete all the trials within 20 min, the experimenter stopped the task. Only two participants failed to complete the tests in one of the two sessions; no participants failed to complete both sessions. In all cases, at least 55 trials were completed.



Imagine you are at the carousel and
facing the jungle gym.

Point to the fountain, then click the mouse button.

Figure 3. The judgments of relative direction task.

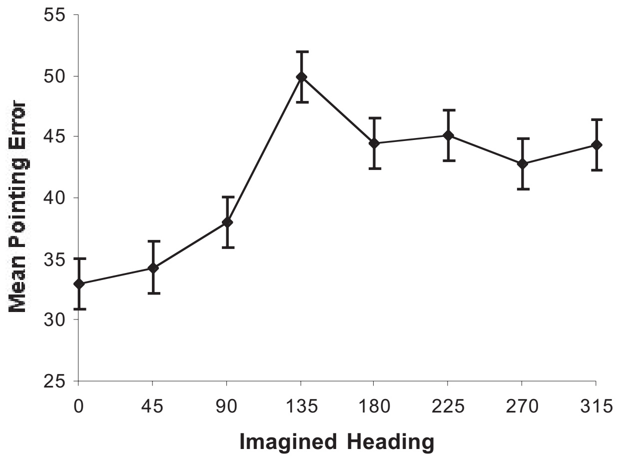


Figure 4. Mean angular error as a function of imagined heading. Error bars reflect ± 1 standard error of the mean.

Test battery. After each movie was encoded and each JRD test completed, the experimenter administered the battery of tests, in the following order: 3 Mts., Symbol Digit, MRT, Road Map Test, Spatial Perspective Test, Questionnaire, Reading Passages, Spatial Span, Digit Span, and Word Span. The order was kept consistent across subjects in an effort to keep any effects of fatigue consistent across individuals.

Results

Group Analyses of Mean Angular Error

Mean angular error of pointing was computed for each participant in each condition. These means were subjected to a split-plot factorial analysis of variance, with encoding perspective (route/survey) and imagined heading (0° to 315°) as within-subjects factors and gender as a between-subjects factor (α = .05). The main effect of perspective was significant, $F(1, 38) = 9.97$, $p = .003$, with error after route encoding ($M = 44.21$, $SE = 1.45$) larger than error after survey encoding ($M = 38.89$, $SE = 1.41$). As expected, the effect of imagined heading was significant, $F(7, 266) = 11.17$. Figure 4 shows error in JRDs as a function of imagined heading. The 0° (preferred) heading was associated with less error than all other (nonpreferred) headings, $F(1, 266) = 22.72$. The main effect of gender was significant, $F(1, 38) = 5.96$, with men ($M = 34.1$, $SE = 1.28$) performing more accurately than women ($M = 49.0$, $SE = 1.46$) overall. No interactions among these factors were significant.

Correlational Analysis

Simple correlations were performed between mean errors for JRDs after route and survey encoding and the spatial skill tasks (α = .05, corrected for multiple comparisons). Mean pointing error for route and survey were highly correlated, $r = .88$. Correlations of route and survey pointing error with skill tests are shown in Table 1. All spatial skill tests that correlated with mean error after encoding from one perspective also correlated with mean error

Table 1
Correlations Between Skill Tests and Pointing Error on Judgments of Relative Direction

	Route	Survey
Spatial tests		
Mental Rotation Test	−0.649*	−0.749*
Road Map Test	−0.474*	−0.527*
Spatial Perspective	0.573*	0.677*
3 Mountains	−0.534*	−0.584*
Spatial Span	−0.510*	−0.600*
Questionnaire	−0.130	−0.124
Nonspatial tests		
Symbol Digit	0.008	0.021
Reading Passages	−0.144	−0.186
Word Span	0.041	0.012
Digit Span	−0.225	−0.323

* $p < .05$, corrected.

after encoding from the other perspective. The key spatial skill tests that correlated significantly with route and survey mean error were the MRT, Road Map Test, Spatial Perspective, 3 Mts., and Spatial Span. These tests also were intercorrelated, to a moderate extent (see Table 2). Of note, the only spatial test that did not correlate with mean pointing error was the Questionnaire, which measured individual preferences for route or survey information.

Simple correlations were then conducted between errors for JRDs after route and survey encoding and nonspatial skill tests. No nonspatial tasks correlated with route or survey mean pointing error. The only significant correlation among nonspatial tasks was between Word Span and Digit Span ($r = .38$, $p = .02$).

Gender Differences

Two sample t tests were conducted on each of the spatial and nonspatial skill tests to assess gender differences ($\alpha = .05$, two-tailed). As shown in Table 3, men outperformed women on the MRT, $t(38) = 2.02$, and the Road Map Test, $t(38) = 2.02$, whereas women outperformed men on the Reading Passages test, $t(38) = 2.02$. No other skill tasks showed gender differences.

Table 3
The Effect of Gender on Individual Skill Tests

Test	Men	Women
MRT	23.15 (6.83)	15.15 (5.83)*
Road Map Test	18.4 (6.63)	12.05 (4.89)*
Spatial Perspective	23.75 (20.59)	23.27 (11.31)
3 Mountains	92.85 (6.77)	86.99 (14.24)
Spatial Span	48.3 (20.29)	45.85 (16.81)
Questionnaire	−.035 (2.7)	−2.3 (3.6)
Symbol Digit	68.95 (9.71)	68.85 (8.57)
Reading Passages	16.5 (2.4)	18.2 (2.4)*
Word Span	4.55 (1.15)	4.6 (.88)
Digit Span	5.75 (1.21)	5.6 (1.43)

Note. Mean raw scores (standard deviations) are shown.
* $p < .05$.

Multiple Regression

Because of the main effect of gender on mean pointing error and on the subset of aforementioned tasks, we conducted separate analyses for each sex, regressing mean pointing error against each of the spatial skill tests that were found to correlate with mean pointing error. There were no differences between the analyses of men and women, and the results were consistent with the analyses when groups were combined. For ease of explication, we present the data from the combined analysis.

Table 2
Intercorrelations Among Spatial Skill Tests

	MRT	Road Map	Spat. Persp	3 Mts.	Spatial Span
MRT	1				
Road Map Test	0.51***	1			
Spatial Perspective	−0.47**	−0.44**	1		
3 Mountains	0.53***	0.32*	−0.38*	1	
Spatial Span	0.42*	0.28	−0.46**	0.11	1
Questionnaire	0.11	0.25	−0.14	0.11	−0.002

Note. MRT = Mental Rotation Test.
* $p < .05$. ** $p < .005$. *** $p < .001$.

A simultaneous linear regression analysis was conducted to determine how the scores on the five spatial skill tests that were found to correlate with mean errors after route and survey encoding predicted mean error. By regressing each spatial test against mean error after route and survey encoding, we were able to examine whether these variables contributed in different ways to the two different perspectives.

A model predicting mean error after route encoding from the MRT, Road Map, Spatial Perspective, 3 Mts., and Spatial Span tasks was significant, $F = 10.06$, $p = .0001$, and accounted for nearly 60% of the variance in the data ($R^2 = .597$). The model predicting mean error after survey encoding from the same five factors was also significant, $F = 25.02$, $p = .0001$, and it accounted for nearly 79% of the variance in the data ($R^2 = .786$). See Table 4 for a summary of the simultaneous regression models

Table 4
Simultaneous Regression Models for Error After Route and Survey Encoding

Variable	Regression Weight	Std Error	t	p value	sr^2
Route model					
Intercept	118.75	25.36	4.68	0.000	—
Spatial Span	−0.31	0.16	−1.99	0.055	.047
3 Mts	−0.51	0.26	−1.98	0.056	.046
MRT	−0.77	0.45	−1.71	0.096	.035
Spat. Persp.	0.24	0.19	1.32	0.196	.021
Road Map	−0.34	0.44	−0.78	0.442	.007
Survey model					
Intercept	108.96	17.07	6.38	0.000	—
Spatial Span	−0.33	0.10	−3.13	0.004	.061
MRT	−0.89	0.30	−2.95	0.006	.055
3 Mts	−0.46	0.17	−2.62	0.013	.043
Spat. Persp.	0.31	0.13	2.47	0.019	.038
Road Map	−0.26	0.29	−0.88	0.384	.005

Note. MRT = Mental Rotation Test.

Table 5
Summary of Forward Stepwise Regression for Mean Error

Variable	Step	ΔR^2	Model R^2	C(p)	F	*p* value
Route model						
MRT	1	0.422	0.422	12.761	27.703	.000
Spatial Perspective	2	0.091	0.512	7.108	6.889	.013
3 Mountains	3	0.030	0.542	6.581	2.357	.133
Spatial Span	4	0.047	0.590	4.604	4.023	.053
Road Map	5	0.007	0.597	6.000	0.604	.442
Survey model						
MRT	1	0.561	0.561	33.902	48.483	.000
Spatial Perspective	2	0.134	0.695	14.564	16.258	.000
Spatial Span	3	0.043	0.737	9.776	5.849	.021
3 Mountains	4	0.044	0.781	4.778	7.043	.012
Road Map	5	0.005	0.786	6.000	0.778	.384

Note. MRT = Mental Rotation Test.

(factors are listed in the order of decreasing squared semipartial coefficient).

To further investigate the connections between the skill scores and mean error, a forward stepwise regression was run for mean error after route and survey encoding. Forward stepwise regression is a model-building method that adds factors in order, based on which factor will contribute more to the model at each step. The results of these regressions are summarized in Table 5. The two most powerful loading factors (added first into the stepwise regression) were MRT and Spatial Perspective, for mean error after both route and survey encoding; however, the loading order of the remaining factors was different. The 3 Mts. task was a higher priority predictor for the route model than Spatial Span. The opposite was the case for the survey model. This further illustrates that whereas route and survey processing may draw upon a common set of skills, the priority of importance of these skills may differ.

Cost Variables

The overall mean pointing error was calculated to be the mean of judgments made from both preferred and nonpreferred headings, and mean error for route and survey was found to change together across individuals. However, looking only at mean error limits, any examination of the effects of transformation from preferred to nonpreferred headings. The key measures of environmental learning performance in this paradigm, the JRDs, are transformation-dependent, that is, imagined heading has a significant main effect overall, with 0° as the preferred heading. As such, we were interested in investigating the difference in performance between judgments made from preferred headings versus nonpreferred headings. This variable, termed change-of-heading cost, was calculated for the different perspectives for each participant as the difference in error at 0° (the preferred heading) and error at nonzero headings.[4]

Unlike the mean errors after route and survey encoding, change-of-heading costs after route and survey were not as highly correlated ($r = .32$, $p = .02$). In other words, whereas mean error after route and survey encoding is likely to maintain the same relationship across individuals (route worse than survey), the transformational costs of route and survey are less consistent across individuals. This difference might mean that transformational processes after either route or survey encoding are differentially affected by a given individual's skills.

To examine this influence of spatial skills on change-of-heading cost, we again computed simple correlations and ran a forward stepwise multiple regression for change-of-heading costs after route and survey encoding. MRT scores correlated with survey change-of-heading cost but not with route change-of-heading cost. Correlations between spatial test scores and change-of-heading costs are shown in Table 6. In the multiple regression, the linear model best predicting change-of heading cost after route encoding included two independent variables: the scores from Spatial Perspective and Spatial Span. This model was significant, $F = 6.72$, $p = .003$, but did not account for much variance ($R^2 = .27$). The model best predicting change-of-heading cost after survey encoding included three variables: the scores on Spatial Perspective, MRT, and 3 Mts. This model also was significant, $F = 5.95$, $p = .002$, and accounted for slightly more variance than the route model ($R^2 = .33$). Regression models for change-of-heading cost variables are summarized in Table 7.

The first variable to load into each model was Spatial Perspective. This finding is consistent with the nature of JRDs in which the transformation from a preferred heading to a nonpreferred heading involves a perspective switch. However, after Spatial Perspective, different variables loaded into the change-of-heading costs after route and survey encoding. This lends support to the concept that route and survey processes may draw upon different skills in order to carry out transformations in heading.

Discussion

The use of a limited learning paradigm revealed effects that may have been masked in previous studies using overlearning. First, overall route encoding resulting in worse performance than survey encoding. Performance after both route and survey encoding can reach equivalent levels, as has been demonstrated by overlearning studies, but it appears that environments viewed from a survey

---

[4] This assumption that headings of 0° are preferred comes from a growing body of work demonstrating orientation dependence in route and survey learning (see Shelton & McNamara, 2004, for review).

Table 6
Correlations Between Change-of-Heading Costs and Spatial Skill Tests

	Route cost	Survey cost
MRT	−0.21	−0.44*
Road Map	−0.29	−0.27
Spatial Perspective	0.50*	0.52*
Spatial Span	−0.34	−0.33
3 Mts.	−0.17	−0.21
Questionnaire	−0.05	−0.04

Note. MRT = Mental Rotation Test.
* $p < .05$, corrected.

perspective may be learned more rapidly. This would seem to suggest that the fastest way to learn how to accurately make judgments of relative direction in a large-scale environment might be to study a map of the environment. Why might this be the case? Perhaps the direct visual experience of the global layout of an environment afforded by a survey perspective may speed processing. On the other hand, when learning an environment from a route perspective, global layout must be inferred, which may add another step to the learning process. Second, limiting the amount of time spent learning an environment also revealed an unexpected difference between genders. Traditionally, this paradigm has failed to find a difference between genders in conditions of overlearning, despite the extensive literature on gender differences in spatial performance (see Montello et al., 1999, for a review). Men and women can learn environments equally well in conditions of overlearning, but it may take women more time to learn an environment thoroughly. Future studies may examine the progression of learning over time and address how this progression might differ in men and women.

The wider range of performance on the JRD task afforded by limited learning allowed us to investigate the relationship between individual differences in spatial skills and performance after route and survey encoding. All spatial skills that correlated with mean overall pointing error seemed to correlate with error after encoding from both route and survey perspectives. These key spatial skills were mental rotation, perspective taking, and spatial working memory. Preference for survey-like or landmark information did not appear to be related to error after encoding from either perspective, and none of the nonspatial skills that we selected seemed to have any significant contribution to either route or survey processing. Taken together with the result that errors after route and survey encoding were highly correlated with each other, these results might suggest that a given individual brings the same general processes to bear when retrieving information following route and survey encoding; however, closer examination would suggest otherwise.

Although route and survey processing correlated with the same set of key spatial skills, they did not seem to draw on these skills in the same way. First, the spatial tasks measuring these skills were prioritized differently in a forward regression model predicting mean overall error after route and survey encoding. Second, the regressions for change-of heading cost, designed to reflect transformational processes employed during performance on JRDs, emphasized the differential roles for key spatial skills after route and survey encoding. It is notable that Spatial Perspective score was the most prominent regressor after both types of encoding, which is not surprising, given that the Spatial Perspective task is essentially a JRD task performed from immediate perception rather than memory. Both are intended to measure how well people perform transformations, but they do not specifically require object-based versus perspective transformations.

With regard to different transformations, the MRT score was important for change-of-heading cost aftersurvey but not route encoding. The association between mental rotation and transformations after survey encoding complements the connection found between mental rotation and survey encoding found in previous studies (Pazzaglia & DeBeni, 2001; Shelton & Gabrieli, 2004). As suggested previously, this relationship may reflect the ability to manipulate a map-like representation (i.e., the map as an object).

In the regression for change-of-heading cost after route encoding, the perspective taking was strongest, followed by the contribution of spatial working memory (which did not contribute substantially to transformations following survey encoding). This result suggests that the JRDs after route encoding were more dependent on spatial working memory ability. The route movies do not provide direct visual experience of the global layout of objects in the environment; this must be inferred. One explanation is that better spatial working memory allows one to build a representation that can be used more flexibly during retrieval. It is also possible that working memory has a more direct relationship in that more information from the route encoding may need to be retrieved and manipulated during JRDs. Although the present data cannot differentiate these two alternatives, both explanations support the claim that route processing (encoding or transformations) is more demanding. This claim is also consistent with the general increased error following route encoding.

Overall, the set of spatial skills measured in this experiment were better predictors of performance after survey encoding than performance following route encoding. All survey regression models accounted for more variance in the data than the corresponding route regression models. This difference in the strength of the models may indicate that these skills do not contribute to route-based processing as much as they do to survey-based processing. Perhaps more "route-like" spatial skill tests are needed to find factors that account for more variance in performance following route encoding. One promising potential solution is to do the

Table 7
Summary of Forward Stepwise Regression for Change-of-Heading Cost Variables

Step	Variable	ΔR^2	Model R^2	C(p)	F	*p* value
Route model						
1	Spatial Perspective	0.253	0.253	−0.706	12.842	.001
2	Spatial Span	0.014	0.267	0.638	0.701	.408
Survey model						
1	Spatial Perspective	0.274	0.274	1.064	14.310	.001
2	MRT	0.049	0.322	0.585	2.652	.112
3	3 Mountains	0.009	0.332	2.105	0.507	.481

Note. MRT = Mental Rotation Test.

testing (as well as the encoding) in virtual reality, which better mimics the immersive and first-person nature of route encoding.

The use of desktop virtual environments has become prevalent because they allow for stricter control over learning conditions than learning in the real world. Although previous work has supported the similarity between virtual environments and real-world environments (Montello, Waller, Hegarty, & Richardson, 2004; Ruddle, Payne, & Jones, 1997), caution is still warranted in interpreting our results. For example, route movies in the laboratory may induce a difference between a participant's simulated heading and actual heading, which could potentially create a kind of interference effect that may not be present in real-world exploratory navigation. Similarly, the survey movie differs from maps in that it uses the actual objects in the environment rather than abstract symbols. This difference may make the encoding of the survey perspective easier for some individuals. In this study, however, our intent was not to exactly duplicate real-world spatial learning but to simplify the issue by approximating certain aspects (namely, the perspective) of environmental learning in the real world. These approximations allow us to take some initial steps in understanding skills people can bring to bear under very tightly controlled conditions.

The present study provides the first clear evidence for behavioral performance differences in judgments of relative direction after visual route and survey encoding under conditions in which the amount of exposure was kept equivalent. Furthermore, it was found that the two perspectives were differentially affected by individual spatial skills, particularly in the areas of transformational processing and working memory demands. Future studies will investigate how these key spatial skills might correlate with neural activity during route and survey encoding and retrieval. Ultimately, this will help pave the way for a thorough understanding of the different ways that individuals learn about large-scale environments.

References

Allen, G. (1999). Spatial abilities, cognitive maps, and wayfinding: Bases for individual differences in spatial cognition and behavior. In R. G. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 46–80). Baltimore: Johns Hopkins University Press.

Allen, G. L., Kirasic, K. C., Dobson, S. H., Long, R. G., & Beck, S. (1996). Predicting environmental learning from spatial abilities: An indirect route. *Intelligence, 22,* 327–355.

Cohen, J., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using Macintosh computers. *Behavior Research Methods, Instruments & Computers, 25(2),* 257–271.

Denis, M., Pazzaglia, F., Cornoldi, C., & Bertolo, L. (1999). Spatial discourse and navigation: An analysis of route directions in the city of Venice. *Applied Cognitive Psychology, 13,* 145–174.

Galea, L. A. M., & Kimura, D. (1993). Sex differences in route-learning. *Personality and Individual Differences, 14,* 53–65.

Hegarty, M., & Kozhevnikov, M. (1999). Spatial reasoning abilities, working memory, and mechanical reasoning. In J. S. Gero & B. Tversky (Eds.), *Visual and spatial reasoning in design* (pp. 1–19). Sydney: Key Center of Design, Computing, and Cognition.

Hegarty, M., Richardson, A. E., Montello, D. R., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence, 30,* 425–447.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence, 32,* 175–191.

Hirtle, S. C., & Hudson, J. (1991). Acquisition of spatial knowledge for routes. *Journal of Environmental Psychology, 11,* 335–345.

Jonides, J., Sylvester, C. C., Lacey, S. C., Wager, T. D., Nichols, T. E., & Awh, E. (2003). Modules of working memory. In R. H. Kluwe & G. Lüer (Eds.), *Principles of learning and memory* (pp. 113–134). Cambridge, MA: Birkhäuser.

Just, M. A., & Carpenter, P. (1985). Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review, 92,* 137–172.

Kail, R. (1991). Controlled and automatic processing during mental rotation. *Journal of Experimental Child Psychology, 51,* 337–347.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition, 29,* 745–756.

Kozlowski, L. T., & Bryant, K. J. (1977). Sense of direction, spatial orientation, and cognitive maps. *Journal of Experimental Psychology: Human Perception and Performance, 3,* 590–598.

La Pointe, L. B., & Engle, R. W. (1990). Simple and Complex Word Spans as Measures of Working Memory Capacity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 1118–1133.

Mellet, E., Bricogne, S., Tzourio-Mazoyer, N., Ghaëm, O., Petit, L., Zago, L., et al. (2000). Neural correlates of topographic mental exploration: The impact of route versus survey learning. *NeuroImage, 12,* 588–600.

Moeser, S. D. (1988). Cognitive mapping in a complex building. *Environment and Behavior, 20,* 21–49.

Money, J., & Alexander, D. (1966). Turner's syndrome: Further demonstration of the presence of specific cognitional deficiencies. *Journal of Medical Genetics, 3,* 47–48.

Montello, D. R., Lovelace, K. L., Golledge, R. G., & Self, C. M. (1999). Sex-related differences and similarities in geographic and environmental spatial abilities. *Annals of the Association of American Geographers, 89,* 515–534.

Montello, D. R., & Pick, H. L. (1993). Integrating knowledge of vertically aligned large-scale spaces. *Environment and Behavior, 25,* 457–484.

Montello, D. R., Waller, D., Hegarty, M., & Richardson, A. E. (2004). Spatial memory of real environments, virtual environments, and maps. In G. L. Allen (Ed.), *Human spatial memory: Remembering where* (pp. 251–285). Mahwah, NJ: Erlbaum.

Mumaw, R. J., Pellegrino, J. W., Kail, R. V., & Carter, P. (1984). Different slopes for different folks: Process analysis of spatial aptitude. *Memory & Cognition, 12,* 515–521.

O'Dekirk, J. M., Wyatt, B. S., & Ellis, N. R. (1993). Individual differences in location memory. *Bulletin of the Psychonomic Society, 31,* 66–68.

Passini, R. (1984). Spatial representations: A wayfinding perspective. *Journal of Environmental Psychology, 4,* 153–164.

Pazzaglia, F., & De Beni, R. (2001). Strategies of processing spatial information in survey and landmark-centred individuals. *European Journal of Cognitive Psychology, 13,* 493–508.

Piaget, J., & Inhelder, B. (1967). *The child's conception of space*. New York: Norton.

Richardson, A. R., Montello, D. R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps, and from navigation in real and virtual environments. *Memory & Cognition, 27,* 741–750.

Ruddle, R. A., Payne, S. J., & Jones, D. M. (1997). Navigating buildings in 'desk-top' virtual environments: Experimental investigations using extended navigational experience. *Journal of Experimental Psychology: Applied, 3,* 143–159.

Schwartz, N. H., & Phillipe, A. E. (1991). Individual differences in the retention of maps. *Contemporary Education Psychology, 16,* 171–182.

Shelton, A. L., & Gabrieli, J. D. E. (2002). Neural correlates of encoding space from route and survey perspectives. *Journal of Neuroscience, 22,* 2711–2717.

Shelton, A. L., & Gabrieli, J. D. E. (2004). Neural correlates of individual differences in spatial learning strategies. *Neuropsychology, 18,* 442–449.

Shelton, A. L., Jambulingam, & Clark, D. (2005). *Self-evaluated learning in route and survey perspectives*. Manuscript in preparation.

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

Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive Psychology, 43,* 274–310.

Shelton, A. L., & McNamara, T. P. (2004). Orientation and perspective dependence in route and survey learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30,* 158–170.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171,* 701–703.

Sholl, M. J. (1988). The relationship between sense of direction and mental geographic updating. *Intelligence, 12,* 299–314.

Smith, A. (1968) The symbol-digit modalities test: A neuropsychologic test of learning and other cerebral disorders. In J. Helmuth (Ed.), *Learning disorders.* Seattle, WA: Special Child Publications.

Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology, 14,* 560–589.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47,* 599–604.

Weisman, J. (1981). Evaluating architectural legibility: Way-finding in the built environment. *Environment and Behavior, 13,* 189–204.

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock–Johnson III tests of achievement.* Itasca, IL: Riverside Publishing.

Zacks, J., Mires, J., Tversky, B., & Hazeltine, E. (2000). Mental spatial transformations of objects and perspectives. *Spatial Cognition and Computation, 2,* 315–332.

Zacks, J., Rypma, B., Gabrieli, J. D. E., Tversky, B., & Glover, G. H. (1999). Imagined transformation of bodies: An fMRI investigation. *Neuropsychologia, 37,* 1029–1040.

Received January 21, 2005
Revision received October 14, 2005
Accepted January 10, 2006 ■