The Influence of Route Planning and its Execution on Spatial Learning

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Abstract

We propose that spatial inferences made during planning and executing a route influence the learning of relative locations through wayfinding. In Experiment 1, separate and combined route plans were compared. The results suggest that inferring multiple directions during the initial stage of planning leads to more accurate representations of relative locations than planning a single route. In Experiment 2, regular and irregular updating modes during the execution phase were compared. The results suggest that irregular updating, which involves multidirectional self-to-object updating, also leads to more accurate representations than regular updating. We conclude that the requirement to make spatial inferences about multiple multidirectional metric interconnections in egocentric reference frames during wayfinding facilitates spatial learning.

Keywords: spatial learning; route planning; wayfinding; egocentric reference frames

Introduction

The means by which humans and animals develop knowledge about their surrounding environments has been a controversial topic for a long time. One theory of the development of spatial knowledge assumes a qualitative change from route knowledge to survey-type knowledge over time (Siegel & White, 1975), and thus the knowledge should become more elaborate as experiences of traveling increase. It is also thought that the qualitative change could occur by automatic and unconscious reorganization of the route knowledge (Thorndyke & Hayes-Roth, 1982). However, there are studies that showed that experiences of an environment do not facilitate spatial learning automatically (Moeser, 1988; Rossano & Reardon, 1999), and repetitive learning does not always efficiently promote the accurate development of knowledge (Ishikawa & Montello, 2006).

The present study examines the relationship between human spatial learning and route planning during wayfinding. Though wayfinding includes a wide range of cognitive activities and behaviors (Gärling, Böök, & Lindberg, 1984), after a destination has been set the basic process of wayfinding is planning and executing of a route in which one decides on and follows between a point of origin and a destination (Golledge, 1999). Specifically, we focused on route planning when moving through environmental spaces such as cities or the interior of buildings. In previous studies, route planning, which incorporates factors such as "short cuts", is often used as a dependent variable that changes with the development of spatial cognition. However, to our knowledge, no study has yet examined the effects of route planning on spatial learning.

Here we assume that spatial inferences during planning and executing a route facilitate the learning of relative locations. This might sound paradoxical because knowledge of relative locations is often thought to be a precondition for planning. Spiers & Maguire (2008) pointed out that when planning a route, the relative direction from the origin to the destination is determined before a specific path can be chosen. In the case when very little is known about a particular environment, how is it possible to find the way to a destination that is out of sight? Given that, to facilitate wayfinding, spatial knowledge of a particular environment is manipulated using rules of inference (Kuipers, 1978). A relative direction must be inferred by representing and manipulating the incomplete knowledge that has already been acquired. For example, when one is not sure which path to take at a four-way intersection in an unfamiliar environment, he or she can express a vague direction to a destination by pointing a finger, which is a spatial inference that people make routinely in their daily lives. The core idea in this study is that the inference of this type will be effective to develop spatial knowledge.

The relationship between relative locations can be described in either an environmental reference frame (object-to-object relations) or an egocentric reference frame (self-to-object relations). However, when deciding on a direction of movement within an environment during wayfinding, it is necessary for a traveler to represent one's body and the destination in an egocentric reference frame (Sholl, 1996) in order to translate one's spatial knowledge into action. On theoretical grounds, self-to-object relations can be represented in a number of ways, for example, as location-dependent reference direction (Poucet, 1993) or in a network of reference frames (Meilinger, 2008). However, the representations commonly contain metric information, defined as the direction and distance from one place to another.

Our expectation was that spatial inferences about self-to-object metric relations would have a facilitating effect when planning a route and updating self-position and orientation at the decision point (e.g. intersections). Gärling et al. (1984) suggested that metrical relations only between important reference points are represented for travel. Naturally, an origin and a destination are such reference points for determining a route at the initial stage. In addition, the decision point should also be the key reference point for following the route. Unlike on-line-type spatial inferences such as narrowly defined path integration, which are based on continuous updating, people pay attention to metric relations during wayfinding mostly when the need arises such as when one chooses a path at the decision point.

Two experiments were conducted to compare incidental learning outcomes when planning and executing different types of the routes using a direction estimation post-test that reflects the structure of self-to-object representations.

In Experiment 1, separate and combined route plans were compared. We assumed that number of the goal directions that participants were required to infer at the start would affect their learning of relative locations within an environment. When a traveler is visiting multiple places, if he or she makes separate route plans (i.e. plan a route to the first place, move to that place, and then plan the route to the next one), one will just compute one direction each time. In contrast, to make a combined route plan for the complete round of visits, the traveler would have to consider multiple interconnections between the origin and the destinations at the same time and effectively learn the interconnections.

In Experiment 2, two types of order of visiting, which led to regular or irregular updating, were compared. In regular updating one constantly updated one's position to destinations situated in the same self-to-object relation. In irregular updating the destinations were situated in multidirectional self-to-object relations. We assumed that a requirement for different types of directional inference when updating would also affect learning relative locations. If a traveler has to infer multidirectional self-to-object relations through the updating process, rather than constantly updating, they would be able to utilize egocentric reference frames over a wide range of the environment.

The Environments and Settings

A real environment was used to observe spontaneous spatial inferences. Additionally, to achieve a natural response from the participants, we set up the wayfinding task as a role-playing game that involved stories (Appendix A). The experiments took place on the campus of Waseda University with participants aged 18 and older attending a school festival and agreeing to participate in the experiments.

Experiment 1

Method

Participants Out of a total of fifty-six participants, who were randomly assigned to each group (Single-Goal or Multiple-Goals), fifty people (mean age 22.0) were included in the analyses. Three women in the Multiple-Goals group made errors in the wayfinding task and were excluded from the analyses. Thus the last three female participants in the Single-Goal group were also excluded, so that both groups contained 25 people with the same male-to-female ratio (9:16).

Materials Labyrinth 1 (7 by 7 meters) was built in a classroom using identical fiberboard sheets (Figure 1, left panel; each panel was 2 meters long and 1 meter wide). Figure 2 shows the layout of the labyrinth and the locations of the four targets, which corresponded to computer displays that showed illustrations of the four residents in the story (Appendix A) and instructions for the wayfinding task. No two displays could be seen at the same time. We developed two programs that were written in Visual Basic for Applications: one controlled the task and recorded the responses, and the other was used for the post-test. The left panel in figure 3 is an example of the operation screen used in the post-test to record the judgments of the participants.

Figure 1: Images of the Labyrinth

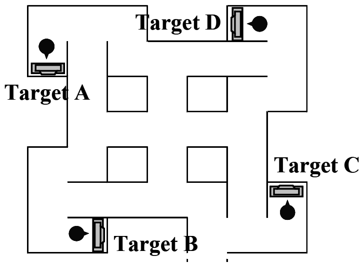


Figure 2: Layout of Labyrinth 1

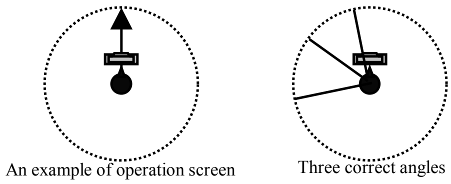


Figure 3: An operation screen and correct angles

Order of Visiting The orders were devised so that the participants did not encounter the same positional relations (Table 1).

Table 1: Orders of Visiting

	First round		Second round
1.	Target A→B→C→D→A	and	A →D→C→B→A
2.	Target A→D→C→B→A	and	A →B→C→D→A
3.	Target A→B→D→C→A	and	A →C→D→B→A
4.	Target A→C→D→B→A	and	A →B→D→C→A
5.	Target A→C→B→D→A	and	A →D→B→C→A
6.	Target A→D→B→C→A	and	A →C→B→D→A

Procedure The wayfinding task consisted of two phases: (i) exploring and (ii) visiting (two rounds). The participants were escorted individually from an anteroom to the labyrinth by an experimenter, who monitored the progress of the task from outside the labyrinth.

During the exploring phase, the participants walked around freely and found the four computer displays. When they found a display, they pressed a keypad that was placed in front of each display (Figure 1, right panel). The visiting phase started when the participant found the last display.

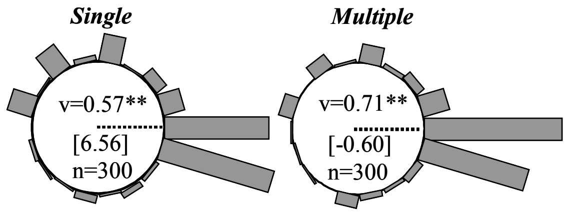
This formed the point of origin of the visiting phase; the point of origin varied depending on how the individual had explored, but because the labyrinth was fully symmetric, each order of visiting involved similar components regardless of the location of the origin. The participants were asked by the resident in the last display to revisit the other residents. In the Single-Goal procedure, only the first target goal was given at the point of origin, and when the participants reached that goal they received the next one. In contrast, in the Multiple-Goals procedure, all three target goals and the order in which they should be visited were given at the point of origin. When the participants reached a target, they pressed the keypad. The task ended after two rounds of revisiting.

After the task, the participants were escorted to another room and took the post-test. They were informed that the experiment included "easy quizzes about your memory and sense of direction". After five filler questions that asked about the story, they were asked to indicate 12 relative directions in the following manner: "if you were standing and facing the target X, indicate the direction of target Y". A computer display used in the test was placed horizontally on a table. The participants viewed the operation screen (Figure 3, left panel) from above and indicated the directions by turning the arrow clockwise or counterclockwise using keypads. The graphic shows a birds-eye view of a participant standing in front of a computer display. Instructions of 12 combinations of X and Y were presented one by one randomly at the top of the screen. Three solid lines in the right panel of Figure 3 shows 3 correct angles for 12 relative directions (there were four groups of 3 directions that had the same correct angle).

Results

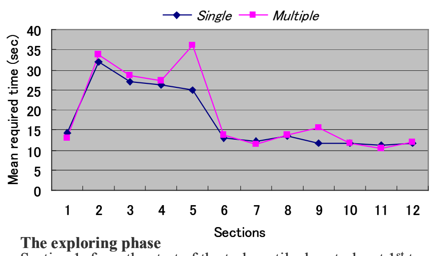
To analyze the 12 relative directions for each group as one data set for each condition, all judgments were adjusted such that the correct angle was 0 degrees. The twelve judgments by each person were analyzed individually to avoid cases where the mean angle corresponded to the correct angle fortuitously (for instance, if two judgments were +120 degrees and –120 degrees, the mean angle would be 0 degrees, the correct angle). Figure 4 shows the mean angles, values for v (a measure of the clustering around a correct direction that decreases as the dispersion increases and varies from –1 to 1), and the results of the V-tests that revealed each data set clustered around the correct angle. The Watson–Williams test revealed that there was no significant difference between the mean angles for the two groups. The accuracy of the judgments was represented by the amount of dispersion, because a greater degree of dispersion meant that more data departed from the correct angle than for a lower value. We compared the dispersions of the two groups by the Mann–Whitney Test, as suggested by Batschelet (1981), and found that the dispersion of Multiple-Goals was smaller than that of Single-Goal (Z=-2.29, p<0.05).

A T test revealed there was no significant difference between the mean total required times for the two groups. Next, we conducted a two-way analysis of variance (ANOVA) on the required time using the following factors: (F1) the number of goals and (F2) sections (see Figure 5). An effect of F2 (F (11,528) =76.40, p<0.01) was observed, together with an interaction between the two factors (F (11,528) =3.05, p<0.01). Student–Newman–Keuls test revealed that among the comparisons between all possible pairs of factor levels, there was only a significant difference between the groups for Section 5 (the first section of the visiting phase). There was no correlation between individual values for v (using 12 judgments per person) and those for the total required time (r=0.13 in Single-Goal and -0.33 in Multiple-Goals).



······· : Correct angles *p<.05 **p<.01
[ ]: mean angles (degree)
plus—counterclockwise direction minus—clockwise direction

Figure 4: Frequency distribution graphs



The exploring phase
Section 1: from the start of the task, until a keystroke at 1st target
2: until a keystroke at 2nd target
3: until a keystroke at 3rd target
4: until a keystroke at 4th target (instructions)
The visiting phase (First round)
Section 5: until a keystroke at the first target visited
6: until a keystroke at the second one
7: until a keystroke at the third one
8: until a keystroke at the 4th target (instructions)
(Second round)
Section 9, 10, 11 and 12: the same as 5, 6, 7 and 8

Figure 5: Mean required time for 12 sections

Discussion

The result that the participants in the Multiple-Goals group performed better in the post-test than those in the Single-Goal group supported the hypothesis that combined route planning facilitates the learning of relative locations. We conclude that inferences about multiple interconnections that were made when planning the route improved the accuracy of the judgments made in the post-test. Detailed analysis of the required time showed that participants assigned to the Multiple-Goals group spent more time on Section 5, during which the participants received their first instructions for the visiting phase and reached the first target.

Presumably, this was because the participants in Multiple-Goals had to recall the relative locations of three targets to make a combined-route plan, as well as having to absorb instructions that contained the next three target goals and the order of visiting. Simultaneously, they had to infer three self-to-object relations from their current position to the targets. In contrast, those in the Single-Goal group had to infer just one direction to the next goal. Thus, the difference in time taken shows the complexity in processing the additional directional inferences in Multiple-Goals as compared with Single-Goal.

In both groups a large proportion of clockwise errors appeared (Figure 4) because angles A and C tended to be considered just in front of and on the right hand side respectively from the imagined standing points of the participants. Though there was no difference between mean angles for the two groups, the angle in Single-Goal containing clockwise error shows that more participants in the group had this tendency than in Multiple-Goals.

After the participants became aware of the position of the target at the initial stage of the planning, they could revisit the targets relatively easily and without taking the wrong path because the shape of the labyrinth gave them a reasonably good view of the access aisles and there were multiple accessible paths. Although the specific pathways that were taken during the task were not recorded in Experiment 1, both conditions involved a similar amount of walking because there was no difference in the total required times between the two groups.

Experiment 2

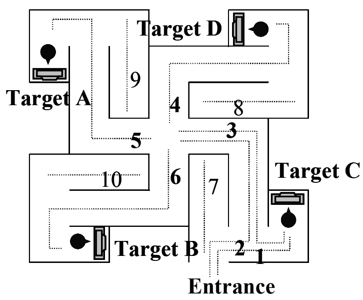
Method

Participants Out of the forty-four participants who were randomly assigned to each group (Circle-Order and Non-Circle-Order), thirty-eight people (mean age, 20.7; male-to-female ratio in each condition, 11:8) were included in the analyses. Three women in each group who made errors in the wayfinding task were excluded from the analyses.

Materials We partially rearranged Labyrinth 1 into the format shown in Figure 6 without changing the locations of the targets and set it up in the same classroom used in Experiment 1. Camcorders were used to record the paths taken by the participants. The other basic materials were the same as those in Experiment 1, except the post-test program the filler questions were redrafted to correspond to the new story (Appendix A).

Order of Visiting Visiting orders 1 and 2 (Table 1) corresponded to the Circle-Order procedure in which the participants visited three targets in a clockwise or counter-clockwise order, for example visiting A→B→C→D→A in the first round, and then A→D→C→B→A in the second round, so that they turned constantly to the right or left at a decision point during each round. The other visiting orders, for example visiting A→B→D→C→A in first round, and then A→C→D→B→A in second round, represented the Non-Circle-Order procedure in which the participant turned right and left turns and going straight ahead at decision points.

Procedure The basic procedure was the same as that of Experiment 1, except that all participants were informed of the three target goals with their visiting order at the point of origin and they carried camcorders during the wayfinding task.



Value for leg 1= 0.5, leg 2=1.5, leg 3, 4, 5, 6=1

Figure 6: Layout of Labyrinth 2

Results

All the judgments were analyzed in the same way as Experiment 1. Figure 7 shows the mean angles, values for v (refer to results of Experiment 1), and the results of the V-tests that revealed each data set clustered around the correct angle. The Watson–Williams test revealed there was no significant difference between the mean angles for the two conditions. The result of the Mann–Whitney Test showed that the Non-Circle-Order group had a smaller degree of dispersion than the Circle-Order group (Z=-3.13, p<0.01).

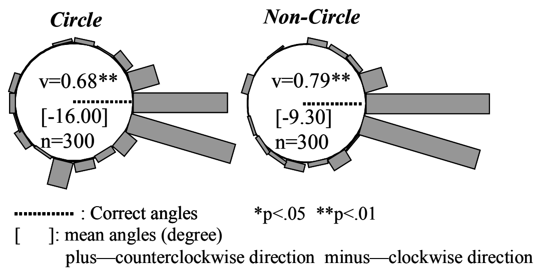


Figure 7: Frequency distribution graphs

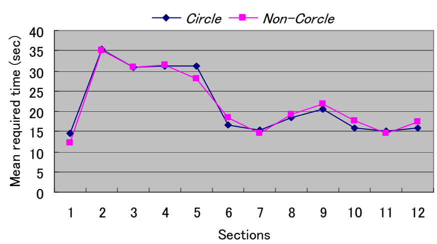


Figure 8: Mean required time for 12 sections

A T test revealed that there was no significant difference between the total required times for the two conditions. We conducted a two-way ANOVA on the required time using the following factors: (F1) the orders of visiting, and (F2) sections (12 levels). We only detected an effect of F2 ($F(11,396) = 43.67$, $p<0.01$) (Figure 8).

The paths that each participant took inside Labyrinth 2 were detailed by video. The aisles of Labyrinth 2 were divided into 10 legs, and to count and compare the amount of walking, we assigned a value to each leg (Figure 6) and summed the values based on the paths taken by each participant, with the exception of legs 7, 8, 9, and 10, which no one walked. The averages of the total were 23.97 in Circle-Order and 23.87 in Non-Circle-Order. T tests revealed that there was no significant difference between them. During the exploring phase, one person in each group seemed to locate the targets first without pressing the keypads; during the visiting phase 12 people (5 in Circle-Order and 7 in Non-Circle-Order) realized that they had gone the wrong way and retraced their steps. We did not exclude these people from the analyses because, during the exploring phase, only one person in each group did not press the keypads immediately, and during the visiting phrase, all the participants remembered the required order and corrected their course. The other participants took the shortest paths of which the total was 22.5. There was no correlation between individual values for v and the following two values: the total required time ($r=0.08$ in Circle-Order and 0.31 in Non-Circle-Order) and the average of the values based on the paths ($r=-0.23$ in Circle-Order and -0.26 in Non-Circle-Order).

Discussion

The result that the participants in the Non-Circle-Order group performed better in the post-test than those in the Circle-Order group supported the hypothesis that irregular updating facilitates the learning of relative locations. We conclude that multidirectional self-to-object updating at decision points improved the accuracy of the judgments made in the post-test.

It is noteworthy that the value for v of the Circle-Order group was equivalent to that of the Multiple-Goals group in Experiment 1. This can be interpreted as a replication of the effect of multiple goals because the participants in both groups planned combined routes. Unlike Experiment 1, it was not possible to execute the plan only with an awareness of the targets' locations because of the fylfot-shaped labyrinth. To reach the next target goal, the participants had to choose one path by updating their positions to the next target at the decision point. Whereas those in the Circle-Order group inferred the same direction to the targets that were always to the right or left of their body in a given round, those in the Non-Circle-Order group had to infer multiple directions to the targets that were backward right, to the right and to the left in a given round.

The length of time spent in the labyrinth and the amount of walking did not show a direct correlation to performance. There were no differences between the groups with respect to, total required time, time in each section and the number of legs that the participants walked during the task.

General Discussion

The results of the experiments revealed that, regardless of physical experience (e.g. the amount of walking and minor differences in both the migration pathways taken and the number of legs walked), the need to infer metric interconnections between multiple points during the initial stage of planning and while executing a route plan improves the accuracy of representations of relative directions within an environment.

The effect of the initial planning in Experiment 1 is consistent with spatial theories and models that propose that the acquisition of representations about spatial structures through wayfinding involves the integration of local perspectives and views that a traveler has learned independently (e.g. Meilinger, 2008; Poucet, 1993; Sholl & Nolin, 1997). The improved accuracy can be interpreted as the consequence of profound and extensive integration because combined route planning involved the representation of greater amounts of local information and the computation of more metric relations in egocentric reference frames at one time than separate route planning. There are navigational strategies that do not involve inferring metric relations. However, in the experimental situations described here the participants were instructed unexpectedly to revisit three unfamiliar targets in a specific order in a completely new environment. They had to recall which display corresponded to which resident and where it was located. In addition, they had to consider object-to-object positional relations between three targets in order to plan a combined route. These combined-route plans, which contained more directional components than those of the simple plans, appeared to facilitate the integration of the local perspectives and views.

We have addressed the question of why regular updating facilitated learning while irregular updating did not in the discussion of Experiment 2. The effect of irregular updating was different from the effect of direct directional inferences to the targets, which was observed in Experiment 1. In Experiment 2, the participants updated their positions relative to the targets at the decision point in the center of Labyrinth 2, and not in front of the displays; however, in the post-test, they were required to estimate directions from the displays. Thus it can be interpreted that the inferences through the updating had a spillover effect on the estimation of self-to-object directions between the targets. We assume that this effect was due to strong interconnections between the decision point and the targets' locations. During irregular updating the decision point, which was one of the key reference points in a spatial structure of Labyrinth 2, was far more important than that of regular updating (as discussed in the next paragraph), and thus it would be strongly interrelated to the other reference points. If we compare the reference point and path to a node and edge, respectively, in a graph, the participants in Non-Circle-Order might have recognized the interrelation of the points as a graph with five nodes and eight edges (e.g. like a square with diagonal lines), while those in Circle-Order have recognized that as a graph with four nodes and four edges (i.e. just a square). Though we do not make a decisive conclusion here, it seems reasonable that the former structure of interrelation would have been more advantageous in representing relative locations in an egocentric reference frame than the latter.

The ineffectiveness of regular updating might be caused by a difference in the hierarchical levels of navigational strategies between the two conditions. Trullier, Wiener, Berthoz, & Meyer (1997) proposed a classification of strategies that is based on levels of complexity of required processing and the information that is perceived, represented, and processed. According to the classification, route following that involves regular updating can be substituted with a lower level strategy that requires the participant to regularly turn left or right at the decision point rather than having to compute a metric relation to choose a path at the decision point each time. Thus, this type of regular decision-making during wayfinding might be ineffective at improving representations of relative directions.

Our findings reflect the natural behavior of humans because our participants in the game-like experiments did not know that they were going to be asked the directions in the post-test. The utilization of inferences for planning and executing a route might be one of the key mechanisms by which individuals refine and modify their representations of relative locations in an environment. Differences in the inferences made might be one of the reasons why "individuals with equal levels of exposure to a place will differ in the extent and accuracy of their spatial knowledge (Montello, 1998)".

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Appendix A

Experiment 1 Labyrinth 1 was set in an imaginary town where a cat and four residents lived: an old lady, an elementary school girl, a vegetable shop owner, and a middle-aged lady. The last resident found by the participants in the exploring phase was determined to be the cat owner. Participants were told by the owner that their cat was missing and were asked to revisit the other residents and get information about the cat.

Experiment 2 Labyrinth 2 was set in an imaginary rural town in Asia where four residents lived: a village headman, a Buddhist monk, an elephant driver, and an old lady. Participants were told by the last resident found that a hidden gem had been stolen by a monkey. Then, the resident asked them to revisit the other residents and get information about the monkey.