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The Role of Internal Information in the Spatial Learning Task through Path Integration

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Abstract

Two experiments were conducted to investigate the role of internal information. The path completion task revealed that internal (vestibular and kinesthetic) information facilitates the accuracy of the homing direction, especially when the number of turns increases. The spatial learning task revealed that the information enhances learning relative locations of points in the path when tracing back on the path is needed to estimate directions. It was concluded that internal information would contribute to forming survey knowledge by providing the homing directions through path integration.

Keywords: path integration; internal information; spatial learning; survey knowledge

Introduction

One of the strategies for navigation and homing is path integration, in which self-velocity and self-acceleration over time are integrated to estimate one's current position and orientation relative to a start point (Mittelstaedt and Mittelstaedt, 1982). In a situation where we travel through a town of narrow streets and cannot see any landmarks, we come to know our location by way of path integration. The sensory sources used in path integration are classified into internal and external information. The internal information consists of physical senses from the vestibular system and kinesthetic sense (proprioception and efference copy). The external information is primarily visual, obtained from the optic flow and the sequence of views that change with one's movement in the environment. By processing the sequence of views, humans can estimate displacements and heading changes (Loomis, Klatzky, Golledge, & Philbeck, 1999).

Although previous studies on path integration have evaluated the contribution of some of the sensory sources in the path integration process, few have focused on how these sources contribute to forming spatial knowledge. When we acquire the knowledge (for instance, relative locations of points on a route) by means of path integration, the process should be linked to spatial learning. The present study is an attempt to examine the role of internal information in both path integration and spatial learning tasks.

Spatial learning through path integration

It has been assumed that path integration is more a process of navigation than spatial knowledge acquisition. Models of path integration mostly employ moment-to-moment updating in which a traveler is continually estimating current positions and orientations relative to a start point in a history-free manner. In this updating, representation underlying the navigation is differentiated from what is referred to as the route and survey knowledge. The representation consists only of the traveler's updated location and orientation, and the traveler cannot retrace the route traveled or come back directly to any point along the route other than its origin (Loomis et al., 1999).

While these processes have been investigated separately in many cases, it is important to suppose that they are combined. This is because the updated estimate might be closely related to spatial learning. The estimate contains the distance and orientation toward a start point, and thus, it naturally provides us with the awareness of the relative location between the current and start point. This awareness in our immediate environment is intimately involved in long-term spatial memory. Since we can update positions at any point relative to any passing point and determine relative locations, these estimates are possibly reflected in forming survey knowledge, interconnections between points. On numerous occasions, we navigate by way of path integration in our day-to-day life: when we walk hallways inside buildings, shopping malls or subway stations. We are actually able to acquire the survey knowledge by walking through streets or hallways even if we do not access some other information like a map that indicates the relative positions of the points in a route.

Contribution of internal information

In path integration tasks, kinesthetic input above and beyond the vestibular one has been presumed to enhance homing accuracy to a varying degree. Sholl (1989) compared vestibular-based and vestibular and kinesthetic-based path integration, and she found that guided walks in an outbound path resulted in much better homing accuracy than did passive transport in a wheelchair. Allen, Kirasic, Rashotte & Haun (2004) also found some contribution of kinesthetic input to homing accuracy of younger adults.

Some studies have attempted to examine the contribution of internal information as additional inputs to external ones in spatial learning tasks in which path integration may be involved. Chance, Gaunet, Beall, & Loomis (1998) found that the information facilitates learning the locations of objects in a path. They asked participants to travel a virtual maze in several modes and indicate directions from the terminal location to target objects. Waller, Loomis, & Haun (2004) found that the information enhances spatial learning in a large-scale environment. They asked participants to indicate the direction to and from all possible pairs of landmarks after traveling an 840-m path on a college campus in one of the following modes; Walk (with a view), Sit (only a view) and Smooth (with a view and body turns). Since the participants could not see multiple landmarks on the path at the same time, they figured out the layout by estimating their position at one landmark relative to the others.

The hypotheses and the tasks

The previous studies suggest that the additional internal inputs resulted in the accuracy of homing direction (Allen et al., 2004; Sholl, 1989) and the facilitation of spatial learning (Chance et al., 1998; Waller et al., 2004). As yet, it is not clear how the information enhances them and what its intrinsic effect is. To deal with this problem, we need to look at when and how the homing direction is impaired during path integration along a path. As well as the aforementioned studies, most previous studies that have examined human path integration used paths consisting of straight legs and turns. People are often moving along these paths in a town or a building. In such a situation, especially at corners, we may feel the necessity for the updating the homing direction, and we are prone to make a large estimation error that affects the success of navigation. This is because the change of the homing direction is relatively large and quick at turns, while the change is gradual and slow in the legs. This idea that turns cause misestimating correspond with the result of Sholl (1989) that found directional judgments were widely scattered as the number of turns increased.

Consequently, it can be hypothesized that the internal information is primarily used for updating the homing direction especially at corners, and thus it facilitates homing accuracy. Then, comparing the internal information to the external one in terms of the homing accuracy in path completion performance after making a number of turns, we can perform an efficient assessment of each contribution to the updating. Experiment 1 uses paths consisting of three or more turns to assess how well the homing accuracy can be preserved at different levels of path complexity. In Experiment 2, the relation between the homing accuracy and spatial learning is examined. In two experiments, internal inputs are isolated and compared to external visual inputs. The turns are fixed at 90 degrees to observe errors in the estimate rather than in the judgment of the turn angle.

The method of analysis

Theoretically, angular data do not obey the normal distribution and thus ANOVA is not suitable for angular data. In the present study, to test the hypotheses, the fit of several statistical models assuming von Mises distribution (angular analogous of the normal distribution) are compared in terms of the maximum likelihood principle and the AIC (Akaike Information Criterion). AIC is a criterion for selecting a statistical model and is defined by AIC = -2(maximum log likelihood of the model) + 2(number of free parameters of the model). The criterion takes into account both the statistical goodness of fit and the number of parameters that have to be estimated to achieve this particular degree of fit, by imposing a penalty for increasing the number of parameters. Smaller values of AIC indicate the preferred model, that is, the one with the fewest parameters that still provides an adequate fit to the data. (Sakamoto, Ishiguro, and Kitagawa, 1986)

Specifically, conditional models imply that data sets for each factor-level combination are equivalently or differently distributed, and they are compared with each other using AIC. This method is similar to the cluster analysis, i.e., data sets are partitioned into clusters, and the results are interpreted based on statistics for the data sets and the clusters. The statistical analysis will use two measures of dispersion that decrease as dispersion increases: (1)"r" reflects concentration around a mean angle and varies from 0 to 1 and (2)"v" reflects concentration around a correct direction and varies from –1 to 1.

Experiment 1

Experiment 1 is conducted to test whether internal information facilitates updating the estimate of the homing direction at the turns. Participants perform the path completion task with 3, 5, and 7 turns in either internal or external traveling mode. If internal and external information are equally used for the updating, the participants in both conditions should perform equally in each path. On the other hand, if internal information preserves the homing accuracy better than the other, it would be the primary resource for updating.

Method

Participants. The participants were 24 graduate and undergraduate students (12 men and 12 women, mean age 21.1) with normal or corrected-to-normal vision and normal vestibular sensation.

Design. The experiment employed a combination of between-subject and within-subject designs using two factors: traveling mode (*Internal* or *External*) and path segment (3 turns & legs, 5 turns & legs, 7 turns & legs). Half of the participants were assigned to *Internal* (kinesthetic and vestibular senses) and the other half to *External* (optic flow and the sequence of views).

Paths. The three paths had constant 90-degree turns at the ends of all legs including the last leg, while the length of legs was either 1 m or 2 m (Figure 1). The participants traveled the paths both clockwise and counterclockwise. The start point of each path for clockwise travel was the end of leg a, while the start points of the paths for counterclockwise travel were the end of leg c (Path3), e (Path5) and g (Path7). At the end of the paths, the participants turned right for clockwise and left for counterclockwise travel.

Materials. The videos shown in *External* were prerecorded using half scale miniatures of 3 paths (Figure 2). During taping, the experimenter pushed a small cart with a video camera and walked inside the miniatures at the speed of about 25 cm per second (about half the walking speed of participants in *External*). The camera faced the traveling direction, so the videos were equivalent to the view from a person traveling inside the miniatures. Two additional videos were recorded for the practice path (90-degree turn & two 2 m legs, clockwise and counterclockwise) in the same way. Measurement software was designed to record directional judgments and response latencies. The participants handled the software on the computer screen through HMD. Figure 3 is an example of an operation screen that shows a bird's-eye view of a participant at the end points. They indicated the start points by navigating a pointer toward the judged direction.

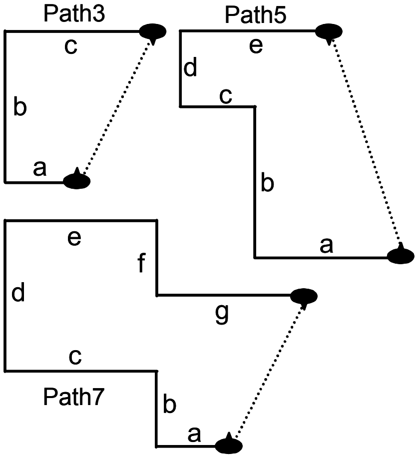

Figure 1: Bird's-eye view of the paths
Correct angles: At the end points, the projecting points of the icons represent participants' frontal directions, and the dashed lines represent correct angles.

Figure 2: Materials in Experiment 1
The right panel is a miniature of Path7. The left panel is an image of the video.

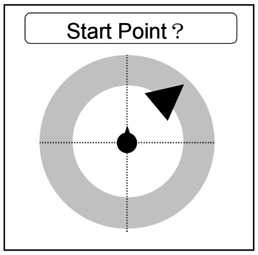

Figure 3: An example of an operation screen

Procedure. One experimenter tested each participant individually. The participants were informed about the pointing task (to indicate the start point after traveling on the paths) and six different paths that had constant 90-degree turns and different length of legs (they did not know that the same path was used twice). Then each participant practiced handling the measurement software. Participants in *Internal* practiced walking blindfolded, where participants walked slowly (at the speed of about 50 cm per second) behind the experimenter with their right hand on the experimenter's shoulder and started or stopped at the call of the experimenter (Figure 4). At the turns, the experimenter put hands on the participants' arms and rotated their body either to the left or right. Then the participants were wheeled to another room with the HMD and earphones with white noise. After practice (triangle completion with 90-degree turn and 2 m legs in both clockwise and counterclockwise travel), the participants performed 6 trials randomly. At the response positions, the participants sat on a wheelchair and indicated the start points, and then they were spun and wheeled zigzag to the next start points. Following their practice with the software, the participants in *External* wore the HMD and the earphones and performed 6 trials randomly after the practice videos (Figure 4). After the experiment, the experimenter asked them how they estimated the homing directions.

Internal *External*

Figure 4: Photographs of the experimenter and participants in each traveling mode

Results

All judgments were adjusted such that correct angles be 0 degrees. Two judgments (clockwise and counterclockwise) per person for each path were analyzed as individual data to avoid cases where the mean angle haphazardly become the correct angle (for instance, if two judgments are +120 degrees and –120 degrees, the mean angle would be 0 degrees, the correct angle). Figure 5 shows mean angles, and values for r and v for distributions of factor-level combinations. Overall, the values for r and v decreased as the turns increased except in *External*-Path5. In each path, the values for r and v were higher in *Internal* than *External* especially in Path5. Figure 5 also shows the results of the Rayleigh and V-tests. The Rayleigh test was designed to determine whether a data set clustered around a mean angle, while the V-test was around a correct angle (Batschelet, 1981). Five distributions except *External*-Path5 were directional (not uniform) and clustered around the correct angles.

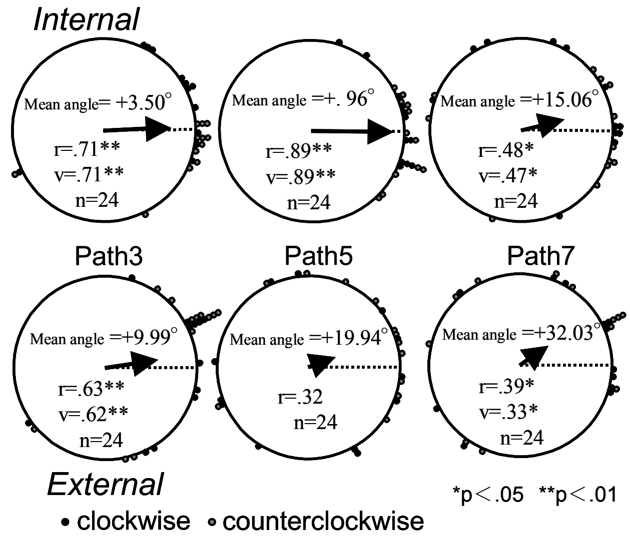

Figure 5: Circular scatter diagrams for the 6 conditions Dashed-lines: correct angles, Direction of arrows: mean angles, Length of arrows: magnitude of r

Table 1: Statistical models and values for AIC

				AIC
M86	I3 E3 r=.67 v=.67	I7 E5 E7 r=.39 v=.36	I5 r=.89 v=.89	412.69
M82	I3 E3 I7	E5 E7	I5	414.33

I:*Internal* E :*External*

Table 2: Mean latencies

msec	Path3	Path5	Path7	Ave.
Internal	5418 (3772)	5608 (5911)	4750 (2168)	5302
External	3627 (2245)	4777 (3043)	5255 (4507)	4553
Ave.	4522	5193	5003	

(SD)

The best-fitting model was M86 among the 203 models generated from all possible combinations that partitioned six data sets into 1 to 6 clusters (Table 1). M82 was the second best model. A two-way ANOVA with mean latencies (Table 2) revealed that there were no main effects and an interaction. The participants' strategies for the estimate were classified into 3 types: (1) keep updating the homing direction, (2) try to remember the shapes of the paths and (3) both strategies (1) and (2) simultaneously. The number of participants for each strategy was as follows: *Internal* (1) 8, (2) 2, (3) 2 and *External* (1) 7, (2) 2, (3) 3.

Discussion

Since most of the participants kept updating the homing directions during the task (strategy-type 1), the errors may reflect the misestimating of the direction with increasing the number of turns and frequency of its large changes, rather than the memory load of the path complexity. The homing accuracy would have influenced by the complexity if many of the participants had tried to remember the path shapes (strategy-type 2) and then recalled the shapes to indicate the directions. In that case, the response latencies would differ between the paths, but the influence is not observed from ANOVA for the mean latencies.

The best-fitting model suggests 3 interpretations. First, the traveling mode seems to have an effect mainly on Path5. Two clusters in M86, [I3, E3] and [I7, E7, E5], show that in Path3 and Path7, *Internal* and *External* data sets are judged to be equivalent. Values for r and v increase as the homing accuracy increases. The r and v for I3 and E3 are relatively similar (Figure 5), and those for I7 and E7 are also similar. Hence, it appears that *Internal* and *External* perform equally in each path. Unlike these paths, I5 and E5 are judged to be different. The r and v are much larger for cluster [I5] than [I7, E7, E5], hence it appears that in Path5, *Internal* performs better than *External* whose performance is as inaccurate as in Path7. Second, the path segment seems to have an effect on Path3 and Path7. Data sets of Path3 and Path7 are judged to be different. The r and v are larger for cluster [I3, E3] than [I7, E7, E5], hence it appears that both *Internal* and *External* perform better in Path3 than in Path7. Third, since the r and v are larger for cluster [I5] than [I3, E3], it appears that the best performance is observed in this condition. It is difficult, however, to conclude whether a combination of Path5 and *Internal* enhances the accuracy from the results.

The second best model suggests that the traveling mode seems to have an effect on Path7 to some extent. In M82, the data set of I7 is judged to be equivalent to those of I3 and E3. In M86, cluster [I3, E3] has a higher r and v than [I7, E7, E5], hence it appears that *Internal* performs better in Path7 than *External*. Comparing I7 with E7, I7 has smaller r and v (Figure 5).

The results suggest that the performance in the path completion of *Internal* is better in Path5 and Path7 than that of *External*. Therefore, it can be concluded that internal information contributes to preserving the homing accuracy in the paths with more than 5 turns. These results indicate that the internal information would be primarily used at the turns and that it facilitates the updating of the homing direction estimate.

Experiment 2

Experiment 2 is conducted to test whether the facilitation of updating is related to spatial learning, using a task in which participants learn the relative locations of 3 points along Path5 in both traveling modes and then judge relative directions. Since directional indications reflect a better understanding of the locations, the indications can be a measure of spatial knowledge status. If the facilitation is related to the spatial learning task, the performance should be better in *Internal* than in *External*.

Method

Participants. The participants were 24 graduate and undergraduate students (12 men and 12 women, mean age 19.9) with normal or corrected-to-normal vision and normal vestibular sensation.

Design. The experiment employed a within-subject design using one factor, traveling mode (*Internal* or *External*).

Paths. Path5 was used twice (clockwise and counterclockwise travel). Figure 6 shows the three points (start-point, halfway-point and end-point) on Path5 in both travels.

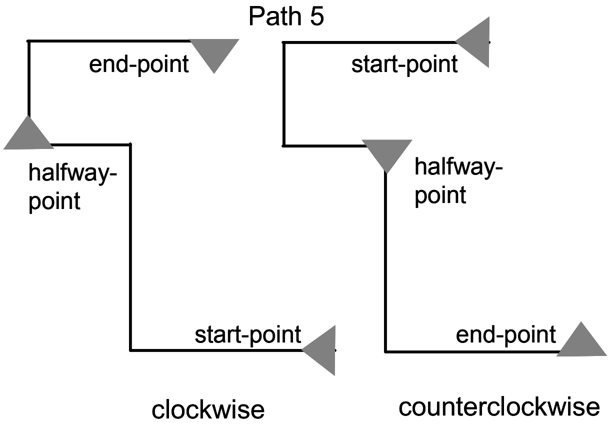

Figure 6: The points in Path5

Materials. Each video of Path5 (clockwise and counterclockwise travel) was divided into two parts. The first videos were from the start-point to the halfway-point, and the second videos were from the halfway-point to the end-point. The measurement software and HMD were the same as those in Experiment 1.

Procedure. The basic procedure was the same as in Experiment 1. The crucial difference was that the participants were asked to learn the relative locations of 3 points in the paths during traveling in Experiment 2. The experimenter stated the points verbally when the participants stood at the start-point and turned at the halfway- and end-point in *Internal*. In *External*, when the first videos started and ended and when the second videos ended, each point was called out. The participants were asked to indicate the 6 relative locations of the three points after learning the path3 times in each traveling mode and then indicated 6 directions randomly. The participants who traveled clockwise in *Internal* traveled counterclockwise in *External* and vice versa. Learning orders and the traveling directions were counterbalanced. The indications was carried out as follows: (1) from the start-point, the participants indicated the other points, as if they had stood at the start-point facing the traveling direction, (2) from the halfway- and end-point, they indicated the other points, as if they had stood at the points after making turns. Six questions asking the relative locations were classified into the following 2 kinds: half of them were homing-questions (asking to trace back along the paths, i.e. from the halfway-point to the start-point and from the end-point to the halfway- and start-points) and the other half were traveling-questions (asking to trace the paths, i.e. from the start-point to the halfway- and end-points and from the halfway-point to the end-point).

Results

All judgments were adjusted to make them comparable and analyzed individually in the same way as in Experiment 1. A total of 4 distributions were obtained crossing the travel mode and question (*Homing* or *Traveling*) factors. Figure 7 shows mean angles, values for r and v, and results of the Rayleigh and V-tests for the distributions. The values for r and v in *External-Homing* were lower than those for the others. All the distributions were directional (not uniform) and clustered around the correct angles.

The best-fitting model was M6 among 15 models generated from all possible combinations that partitioned four data sets into one to four clusters (Table 3). M2 was the second best model. A two-way ANOVA with mean latencies (Table 4) revealed that there were no main effects and an interaction.

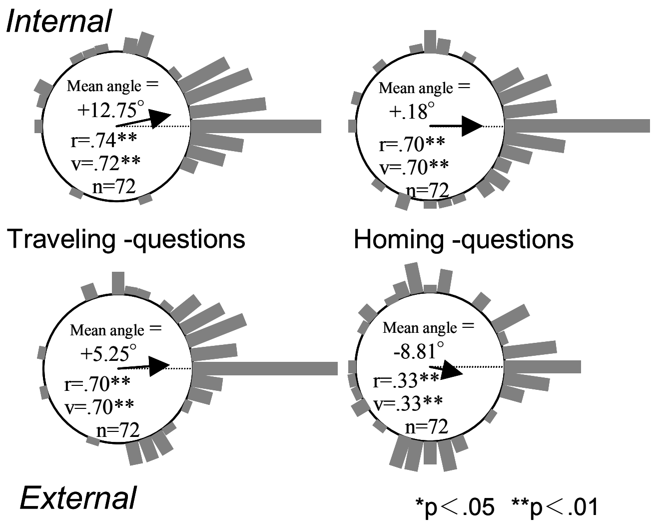

Figure 7: Circular histograms for the 4 conditions

Table 3: Statistical models and values for AIC

					AIC
M6	I·T	I·H	E·T	E·H	792.45
	r=.71 v=.71			r=.33 v=.33	
M2	I·T	I·H	E·T	E·H	797.25

T :*Traveling-Questions* H :*Homing-Questions*

Table 4: Mean latencies

msec	*Traveling-Questions*	*Homing-Questions*	Ave.
Internal	11689 (6224)	10424 (5511)	11057
External	11018 (6102)	10926 (5287)	10972
Ave.	11353	10675	

(SD)

Discussion

The best-fitting model suggests an interpretation that an effect of one factor depends on the levels of the other. Specifically, the traveling mode seems to have an effect on *Homing-Questions*, and the question factor seems to have an effect on *External*. Cluster [I.T, I.H, E.T] in M6 shows that these 3 data sets are judged to be equivalent. The r and v for *Internal-Traveling*, *Internal-Homing* and *External-*

Traveling are relatively similar to each other (Figure 7), hence, it appears that these conditions perform equally. On the other hand, cluster [E.H] shows that the data set is judged to be different from the others. The r and v are considerably smaller for [E.H] than for [I.T, I.H, E.T], hence it appears that the performance under this condition deteriorates markedly.

The results suggest that the performance in *Internal* is better than *External* only when the participants answered the homing-questions. If there is no significant difference of the mean latencies between the questions, the homing-questions should be more difficult than the other because they may require the participants to both trace and retrace the path in order to judge the directions to the passing points against the movement of the participants during the learning phase. These judgments correspond to the estimate of the homing direction by way of path integration. In contrast, the participants answered the traveling-questions that require only tracing and not retracing the path equally accurate regardless of the traveling mode. Therefore, it can be presumed that the estimation of the homing direction is related to the spatial learning task and that the internal information enhances learning the relative locations that need the accurate homing estimation during the learning phase.

General Discussion

The results of Experiment 1 indicate that internal information facilitates the preservation of homing accuracy, especially when the number of turns increases. Hence, the information might be vital to update the homing direction at turns where we are prone to misestimate it. The results of Experiment 2 indicate that this facilitation is related to the performance of the spatial learning task, especially when the estimate of the homing direction is necessary to judge the relative locations. Considering the results together, it can be concluded that the information contributes to spatial learning through path integration by providing the homing directions.

This contribution would explain how the information enhanced spatial learning in the previous studies. This explains why the participants who walked in Chance et al. (1998) could learn and maintain relatively accurate multiple homing directions to several objects in the path after making turns. In Waller et al. (2004), the participants who walked could figure out the layout by estimating relative locations that required retracing the path better than those who just watched the video.

The contribution may also be reflected in forming survey knowledge. As we acquire better understanding of interconnections between points on a route, our spatial knowledge becomes elaborated. For example, if we can indicate the relative locations between points A and B bi-directionally, our knowledge is more elaborate than if it is possible only from A to B. From this point of view, internal information would contribute to forming the survey knowledge by providing the multiple homing directions through path integration.

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