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Path integration: Effect of curved path complexity and sensory system on blindfolded walking

Panagiotis Koutakis [a,b], Mukul Mukherjee [b], Srikant Vallabhajosula [d], Daniel J. Blanke [b], Nicholas Stergiou [b,c,*]

[a] Department of Surgery, University of Nebraska Medical Center, Omaha, NE, United States
[b] Nebraska Biomechanics Core Facility, University of Nebraska at Omaha, Omaha, NE, United States
[c] College of Public Health, University of Nebraska Medical Center, Omaha, NE, United States
[d] Department of Physical Therapy Education, Elon University, Elon, NC, United States

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ABSTRACT

Path integration refers to the ability to integrate continuous information of the direction and distance traveled by the system relative to the origin. Previous studies have investigated path integration through blindfolded walking along simple paths such as straight line and triangles. However, limited knowledge exists regarding the role of path complexity in path integration. Moreover, little is known about how information from different sensory input systems (like vision and proprioception) contributes to accurate path integration. The purpose of the current study was to investigate how sensory information and curved path complexity affect path integration. Forty blindfolded participants had to accurately reproduce a curved path and return to the origin. They were divided into four groups that differed in the curved path, circle (simple) or figure-eight (complex), and received either visual (previously seen) or proprioceptive (previously guided) information about the path before they reproduced it. The dependent variables used were average trajectory error, walking speed, and distance traveled. The results indicated that (a) both groups that walked on a circular path and both groups that received visual information produced greater accuracy in reproducing the path. Moreover, the performance of the group that received proprioceptive information and later walked on a figure-eight path was less accurate than their corresponding circular group. The groups that had the visual information also walked faster compared to the group that had proprioceptive information. Results of the current study highlight the roles of different sensory inputs while performing blindfolded walking for path integration.

1. Introduction

Humans can utilize two distinct strategies for navigation: allocentric and egocentric navigation. Allocentric navigation is associated with the knowledge or memory of landmarks and the ability to orient with respect to a known object or vista of a scene [1]. Animals like honeybees, utilize landmark navigation to locate their hive while humans utilize distinct landmarks when driving [2]. Egocentric navigation is associated with path integration which is the ability to navigate in space using the system itself as a reference [3]. Continuous information of the distance and direction traveled from the system itself are integrated through path integration. Additionally, a homing vector from the starting point is created and updated until reaching the desired endpoint location. It has been demonstrated that desert ants rely on the ability of path integration by foraging along novel routes until they find a food source [4,5]. After reaching the site, desert ants calculate the homing vector to guide them back to the nest. If the desert ant is placed on a new starting location, it will continue to travel along the same (now incorrect) homing vector, demonstrating that distance and direction are updated by egocentric movement cues [6,7]. Similar behavior has been found in birds [8] and mammals [9].

Humans can use different sensory systems for path integration. These sensory systems include visual (optic flow), proprioceptive (feedback from the muscles and the tendons) and vestibular (translational and rotational accelerations) systems. However, the nature of this multi-sensory integration for path integration is unknown. The most commonly used method of investigating path integration is walking blindfolded to a previously seen target (for a review see [10]). In the past, path integration has been studied by estimating the distance and direction traveled from a starting point while walking blindfolded mostly on either a straight [11–13] or a

* Corresponding author at: Nebraska Biomechanics Core Facility, 6001 Dodge Street, Omaha, NE 68182-0216, United States. Tel.: +1 402 554 3247; fax: +1 402 554 3693.
E-mail addresses: nstergiou@unomaha.edu, nstergiou@mail.unomaha.edu (N. Stergiou).

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triangular path [14,15]. The accuracy of path integration in these processes is addressed on the basis of the endpoint of the path. The differences observed between the distance of the actual path and the distance traveled of participants' return path gives a measure of perceived distance, and the angular difference between the direction of that path and the required direction provides a measure of perceived heading.

While path integration-based research has focused on straight line and triangular paths, limited information exists regarding path integration using a circular path. Takei and colleagues found that a circular path was more demanding and required additional attentional control involving multi-sensory inputs [16,17]. The authors suggested that different sensory processes were utilized for the estimation of the length and the curvature (direction) of the path. In theory, otolith stimulation due to rotational forces (i.e. centrifugal) and/or angular position of the lower extremities can provide information about the constant change in the curvature of these paths. Proprioceptive information directly from the feet and/or information from the semicircular canals based on the head orientation could be used to update instantaneous position. However, research in the area of path complexity and how this interacts with sensory information is still scanty. It has been proposed that the proprioceptive system can be used not only to adopt a specific locomotor path but to estimate how far someone rotates during turning [18].

The purpose of the current study was to investigate how sensory information and path complexity affect path integration. Four groups of blindfolded subjects walked on a circular or a figure-eight path which they previously saw or on which they were previously guided. We hypothesized that visual information of the path (previously seen path) would lead to greater accuracy (path length and trajectory) than proprioceptive information (previously guided path). We also hypothesized that in comparison to the more complex figure-eight path, accuracy would be greater on the circular path. Finally, we hypothesized that as complexity of the path increased the difference in accuracy between the groups with visual and proprioceptive information will decrease.

2. Methods

Forty healthy university students from psychology and physical education majors, aged between 19 and 32 years gave informed consent according to the University guidelines (Table 1). The sample size was determined based on our pilot data. We calculated that a sample size of 10 subjects per groups in each of the four groups was sufficient to achieve an 80% power to test the effect of both sensory system and complexity of curved path. Exclusion criteria were neuromuscular or musculoskeletal disorders that could alter gait or present a safety issue, vestibular or ataxic disorders, history of dizziness or medications that can cause dizziness, synesthesia or other disorders affecting the subject's orientation in space. Dizziness was assessed with the Dizziness Handicap Inventory (DHI) questionnaire [19].

The subjects were randomly assigned into four groups/conditions. In the first group (previously seen – circular path condition), the subjects first saw the circular path and then were asked to walk blindfolded on the path while data was collected. In the second group (previously guided – circular path condition), the subjects were blindfolded upon entering into the laboratory and were hand-guided along the circular path. Then, they were asked to walk blindfolded on the path while data was collected. In the third group (previously seen – figure-eight condition), the subjects first saw the figure-eight path and then they were asked to walk blindfolded on the path while data was collected. In the fourth group (previously guided – figure-eight condition), the subjects were blindfolded upon entering into the laboratory and were hand-guided through the figure-eight path. Then they were asked to walk blindfolded on the path while data was collected. Each subject performed only one trial of the respective condition and walked with their shoes. The circular path had a radius of 1.2 m. The figure-eight path had a radius of 1.2 m for each semicircular component and a distance of 1.2 m from the center of the figure to the center of each semicircle [17]. The experiments were conducted in a quiet environment. All the subjects were instructed to retrace the path at their self-selected speed. They were also assured that in lieu of their safety, the experimenter would inform them well in advance if they get close to any of the cameras or the wall while walking blindfolded. The nearest camera tripod was 3.1 m, the nearest wall in the room was 2.87 m and the nearest object (data collection station) was 1.57 m from the perimeter of the circular path. The nearest camera tripod was 1.7 m, the nearest wall in the room was 2.72 m and the nearest object (data collection station) was 1.57 m from the perimeter of the figure-eight path. In addition, all the subjects wore earplugs to avoid auditory interference.

An eight-camera system (Motion Analysis Corp, Santa Rosa, CA) was used to capture the 3D coordinates of a reflective marker placed on the sacrum of the subjects while walking. The data was exported and processed using custom-made Matlab (Mathworks Inc., Natick, MA) routine. This software was used to calculate the dependent measures of average trajectory error, walking speed, and distance traveled from the acquired coordinates for each subject during each condition. The ideal trajectory of the paths was inscribed on the laboratory floor (Fig. 1).

The average trajectory error was calculated as the summation of the deviation error of each point of the walked trajectory from each point of the true predefined trajectory of the path divided by the length of data points of the corresponding trial. The distance traveled was calculated as the overestimation or underestimation of the walked trajectory with the true total distance (7.53 m for the circular path and 14.32 m for the figure-eight path) of the predefined path. Smaller values of trajectory error and distance traveled indicate greater accuracy. Walking speed was calculated as the first derivative of the position data.

A 2×2 ANOVA was used to identify differences between the group means for the dependent variables of average trajectory error and walking speed. The two factors were complexity of the curved path (circular versus figure-eight) and sensory system (visual versus proprioception; previously seen versus previously guided). Post hoc Tukey tests were performed when a significant interaction was identified. For the dependent measure distance traveled, and due to the actual difference between the two paths (7.53 m for circular and 14.32 m for figure-eight), we performed separate independent *t*-tests for each path to compare the groups under previously seen and previously guided conditions. Statistical analysis was performed using SPSS (International Business Machines, Armonk, NY) and the level of significance was set at 0.05.

3. Results

3.1. Average trajectory error

The ANOVA results revealed a significant main effect for the complexity of the curved path factor [$F(1, 36) = 69.75$, $p < 0.0001$]. Both groups of the previously seen and previously guided conditions of the circular path produced much smaller values than the corresponding groups of the figure-eight path (Table 2). There was a significant main effect for the sensory system factor [$F(1, 36) = 14.27$, $p < 0.001$; Table 2]. On an average, subjects produced smaller errors while retracing the path relying on their visual system (previously seen condition; Fig. 2) compared to subjects' performance relying on the proprioceptive information (previously guided condition). In addition, these differences resulted in a significant interaction between the two factors [$F(1, 36) = 26.47$, $p < 0.0001$] (Table 2). Practically, while the trajectory errors for the circular path were relatively similar using both sensory systems, the error for the figure-eight path was greater while using the proprioceptive system (previously guided condition; Fig. 3).

Table 1
Subject demographics for all groups/conditions; each group had ten subjects.

	Age (yrs)	Height (cm)	Mass (kg)	Sex (F/M)	DHI
Circular path – previously seen	22.4 ± 3.03	175.2 ± 11.3	68.3 ± 14.22	5/5	8/100
Circular path – guided	21.8 ± 3.08	168.9 ± 6.68	61.4 ± 6.90	6/4	10/100
Figure of eight path – previously seen	23.5 ± 4.19	169.8 ± 5.78	59.5 ± 7.13	7/3	8/100
Figure of eight path – guided	22.2 ± 4.02	172 ± 7.70	62.1 ± 10.24	7/3	12/100

Note: DHI = Dizziness Handicap Inventory.