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# Path Integration: Effect of Curved Path Complexity and Sensory System on Blindfolded Walking

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1 **Abstract**

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

21 **Keywords:** human navigation, vision, proprioception, spatial performance, locomotion, gait

## 22 **Introduction**

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

37           Humans can use different sensory systems for path integration. These sensory systems  
38 include visual (optic flow), proprioceptive (feedback from the muscles and the tendons) and  
39 vestibular (translational and rotational accelerations) systems. However, the nature of this multi-  
40 sensory integration for path integration is unknown. The most commonly used method of  
41 investigating path integration is walking blindfolded to a previously seen target (for a review see  
42 [10]). In the past, path integration has been studied by estimating the distance and direction  
43 travelled from a starting point while walking blindfolded mostly on either a straight [11-13] or a  
44 triangular path [14,15]. The accuracy of path integration in these processes is addressed on the

45 basis of the endpoint of the path. The differences observed between the distance of the actual  
46 path and the distance travelled of participants' return path gives a measure of perceived distance,  
47 and the angular difference between the direction of that path and the required direction provides  
48 a measure of perceived heading.

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

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

68 increased the difference in accuracy between the groups with visual and proprioceptive  
69 information will decrease.

## 70 **Methods**

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

80 The subjects were randomly assigned into four groups/conditions. In the first group  
81 (previously seen-circular path condition), the subjects first saw the circular path and then were  
82 asked to walk blindfolded on the path while data was collected. In the second group (previously  
83 guided-circular path condition), the subjects were blindfolded upon entering into the laboratory  
84 and were hand-guided along the circular path. Then, they were asked to walk blindfolded on the  
85 path while data was collected. In the third group (previously seen-figure-eight condition), the  
86 subjects first saw the figure-eight path and then they were asked to walk blindfolded on the path  
87 while data was collected. In the fourth group (previously guided-figure-eight condition), the  
88 subjects were blindfolded upon entering into the laboratory and were hand-guided through the  
89 figure-eight path. Then they were asked to walk blindfolded on the path while data was  
90 collected. Each subject performed only one trial of the respective condition and walked with

91 their shoes. The circular path had a radius of 1.2m. The figure-eight path had a radius of 1.2m for  
92 each semicircular component and a distance of 1.2m from the center of the figure to the center of  
93 each semicircle [17]. The experiments were conducted in a quiet environment. All the subjects  
94 were instructed to retrace the path at their self-selected speed. They were also assured that in lieu  
95 of their safety, the experimenter would inform them well in advance if they get close to any of  
96 the cameras or the wall while walking blindfolded. The nearest camera tripod was 3.1m, the  
97 nearest wall in the room was 2.87m and the nearest object (data collection station) was 1.57m  
98 from the perimeter of the circular path. The nearest camera tripod was 1.7m, the nearest wall in  
99 the room was 2.72m and the nearest object (data collection station) was 1.57m from the  
100 perimeter of the figure-eight path. In addition, all the subjects wore earplugs to avoid auditory  
101 interference.

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

108 The average trajectory error was calculated as the summation of the deviation error of  
109 each point of the walked trajectory from each point of the true predefined trajectory of the path  
110 divided by the length of data points of the corresponding trial. The distance travelled was  
111 calculated as the overestimation or underestimation of the walked trajectory with the true total  
112 distance (7.53m for the circular path and 14.32m for the figure-eight path) of the predefined path.

113 Smaller values of trajectory error and distance travelled indicate greater accuracy. Walking speed  
114 was calculated as the first derivative of the position data.

115 A 2x2 ANOVA was used to identify differences between the group means for the  
116 dependent variables of average trajectory error and walking speed. The two factors were  
117 complexity of the curved path (circular versus figure-eight) and sensory system (visual versus  
118 proprioception; previously seen versus previously guided). Post hoc Tukey tests were performed  
119 when a significant interaction was identified. For the dependent measure distance travelled, and  
120 due to the actual difference between the two paths (7.53m for circular and 14.32m for figure-  
121 eight), we performed separate independent t-tests for each path to compare the groups under  
122 previously seen and previously guided conditions. Statistical analysis was performed using SPSS  
123 (International Business Machines, Armonk, NY) and the level of significance was set at 0.05.

## 124 **Results**

### 125 *Average trajectory error*

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

135 circular path were relatively similar using both sensory systems, the error for the figure-eight  
136 path was greater while using the proprioceptive system (previously guided condition; Figure 2).

137

### 138 *Walking speed*

139 The ANOVA results revealed significant differences for the walking speed (Table 2).  
140 There was a significant main effect for the sensory system factor [ $F(1, 36) = 5.67, p < .05$ ] but  
141 not for the complexity of the curved path factor [ $F(1, 36) = 0.062, p = 0.805$ ]. Subjects relying  
142 on the visual system (previously seen condition) walked faster than those relying on the  
143 proprioceptive system (previously guided condition). There was no significant interaction [ $F(1,$   
144  $36) = 0.179, p = 0.675$ ].

145

### 146 *Distance travelled*

147 The distance travelled was significantly larger than the true total distance of 7.53m for  
148 the circular previously seen condition [ $t(9) = 5.26, p < 0.001$ ; Table 2]. In addition, the distance  
149 travelled was significantly larger than the true total distance of 7.53m, for the circular previously  
150 guided condition [ $t(9) = 3.53, p < 0.01$ ]. No significant differences were found with the true  
151 distance of 14.32m for the figure-eight path in both the previously seen and the previously  
152 guided conditions (Table 2). Lastly, no significant differences were found for the distance  
153 travelled between the previously seen and the previously guided conditions for both the circular  
154 (10.70m versus 9.95m) and figure-eight paths (13.83 versus 15.43m; Table 2).

### 155 **Discussion**

156 The purpose of the current study was to investigate how sensory information (visual  
157 versus proprioceptive) and path complexity (circular versus figure-eight) affect path integration.



158 We hypothesized that visual information of the path would lead to greater accuracy than  
159 proprioceptive information. We also hypothesized that the simpler circular path would have  
160 greater accuracy than the more complex figure-eight path. Our results indicated that our  
161 hypotheses for main effects were true for the trajectory error. Further the hypothesis for the  
162 sensory system (visual vs proprioceptive) was true for the walking speed. For the interaction, we  
163 hypothesized that the differences between vision and proprioception would minimize as the path  
164 complexity increases. This hypothesis was false for the average trajectory error.

165         Our results showed that proprioceptive information is not as crucial as visual information  
166 for path integration when we walk a complex curved path like figure-eight. In a previous study,  
167 researchers found that healthy human subjects can accurately reproduce three circular paths of  
168 different radii even when they walk in dim lighting conditions concluding that reproduction of  
169 circular paths is possible without visual information [17]. However, their subjects had both  
170 visual and proprioceptive cues available questioning their conclusions. Our results demonstrated  
171 that during walking on curved paths, path integration relies heavily on visual information. In  
172 contrast with our results, other studies have found that information from proprioception can  
173 provide an accurate representation of the imposed distance [12,20,21]. In these studies, subjects  
174 actively or passively reproduced straight line paths that they were previously guided through.  
175 The simplicity of this type of the path could lead to the predominance of proprioceptive  
176 information for path integration. Therefore, our results suggest that proprioception can provide  
177 only a gross orientation in space when we are walking along curved paths. This explanation  
178 agrees with others who suggested a similar role for proprioception for path integration [10,22-  
179 24].

180 Our results demonstrated that vision is more dominant than proprioception in a figure-  
181 eight path. Specifically, when we compared the figure-eight previously guided condition with the  
182 circular previously guided condition, a significant increase was found in the trajectory error for  
183 the figure-eight path. This suggests that the complexity of the path can significantly affect the  
184 contribution of proprioception to path integration. Support for these results is provided by studies  
185 that explored path integration in more complex paths, such as in longer straight lines and  
186 triangles [12,25]. These studies suggested that returning to the starting location required some  
187 type of an additional record of the outbound path (i.e. hypotenuse) which requires the usage of  
188 additional neural resources from higher control centers [12,25].

189 The distance travelled demonstrated significant differences when we compared the actual  
190 trajectories with the one that the subjects reproduced. Originally, significant differences were  
191 anticipated for both paths and conditions. However, significant differences were found only for  
192 the circular path as the subjects walked more than the actual distance. Participants traversed  
193 0.5m lesser (in previously seen condition) and 1.1m more (in previously guided condition)  
194 compared to the true total distance (14.32m) on the figure-eight path. Though the differences  
195 between the distances travelled in these conditions with the total true distance were not  
196 statistically significant, these numbers show that the subjects were always away from the true  
197 total distance during figure-eight path conditions as well. There was a tendency to undershoot the  
198 distance travelled in the previously seen condition and overshoot the distance travelled in the  
199 guided condition.

200 Walking speed decreased for both paths in the previously guided condition and was  
201 similar across conditions. Bredin et al. found that healthy subjects walking on a straight line  
202 tended to decrease the distance travelled with an increase in walking speed suggesting that the

203 total distance travelled and speed are related [11]. However, our results demonstrated that  
204 differences in walking speed were not the same as that in distance travelled. Distance travelled  
205 did not change between the conditions, while walking speed changed across paths for the  
206 previously seen condition. This difference in walking speed may be an effect of fear of bumping  
207 into the surrounding cameras or even the wall, as the subjects did not have access to a guide. A  
208 similar effect was observed in another study where blindfolded subjects had to complete a  
209 triangular path while driving a mobile robot [26].

210         The differences seen for the average trajectory error and distance travelled variables  
211 between the two curved path conditions (circular and figure-eight) could be attributed to the  
212 difference in complexity of both the paths. The figure-eight is more complex than the circular  
213 path and this complexity could be in terms of the length of information that needs to be  
214 processed or familiarity with the shape/path. Certainly both the paths differ in the amount of  
215 information that needs to be processed as the circular trajectory has only the angular component  
216 but the figure-eight path has both the angular and linear components.

217         In our experiments, subjects had to retrieve information from their different sensory  
218 systems to complete the circular or the figure-eight path. This could have occurred through two  
219 distinct mechanisms. The first mechanism was associated with a visual representation of the  
220 intended path trajectory. The second mechanism was associated with proprioceptive-motor  
221 representation during which the subjects were blindfolded from the beginning and were guided  
222 through the paths. Based on the goal/specifications of the task a motor command was sent to the  
223 lower limbs to fulfill the requirements of the task. The motor command based on the motor  
224 output was reinforced from sensory information gathered from the environment and the organism  
225 itself. Then, the modified command with the reinforced information was transferred to the

226 memory processes. However, there is the possibility that the modified command could also  
227 transfer to the path integration process and provide a new motor output that again could get  
228 reinforced from sensory feedback and get consolidated into memory. Therefore, we hypothesize  
229 that the processing centers of visual and proprioceptive information share a common biological  
230 substrate that affect the planning and execution of a motor command.

231         The results of this study can benefit specific populations. For example, visual- and  
232 hearing-impaired individuals as well as the elderly with vision problems can benefit through the  
233 designing of instruments that will enhance the sensory systems contribution to path integration  
234 and the formulation of cognitive maps. Another group that can benefit is miners. According to  
235 the Mine Safety and Health Administration, the annual average rate of fatalities associated with  
236 underground incidents in 1997 in mining was 56.9% (Mine Safety and Health Administration).  
237 Miners work in risky and hazardous environments. In emergency situations like a mine collapse,  
238 miners may be trapped in the dark trying to find their way to safer areas. Understanding the  
239 contribution of sensory systems in path integration can help in the development of equipment  
240 that will help miners utilize their senses other than vision in order to find their way in the dark  
241 and survive until help arrives. Our future studies will explore the contribution of other sensory  
242 systems like tactile and vestibular systems on path integration.

## 243 **Conclusion**

244         The current study investigated the contribution of vision and proprioception on path  
245 integration during simple and complex curved locomotion. The results indicate that (a) visual  
246 information minimizes error in path integration however complexity of path affects this ability  
247 and (b) the more complex the curved path, the larger the error in path integration and  
248 consequently more is the dependence on external feedback.

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