Research Article

Preliminary Study: The Test Technique for the Evaluation on Spatial Navigation in the Absence of Visual Data in Healthy Individuals

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Highlights

- This test is readily applicable in clinical practice and has been standardized
- Path integration evaluation can be performed without visual data

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ABSTRACT

Background and Aim: Path integration refers to the capability of utilizing self-motion information produced by one's own bodily movements to accurately determine and maintain one's position in space. Typically, path integration mechanisms come into play when visual information is limited or absent. The objective of this study was to develop a path integration test that relies solely on self-motion cues derived from body movements, without the involvement of visual cues.

Methods: The study involved 157 volunteers (86 females and 71 males) aged between 18 and 70 years. Participants were asked to walk on a coordinated ground with their closed eyes and follow the six different commands. They were, after that, requested to return their initial position. Movement time was manually measured by the stopwatch. The distance between the original reference point and estimated starting point was recorded.

Results: The second command that showed the lowest standard deviation out of the six commands given to the participants was observed as the more reliable test among the other commands (47.51±33.75). In addition, the completion time of the second command increased with increasing age ($p<0.001$).

Conclusion: This study introduces an innovative spatial navigation approach utilizing the second command set. As an alternative, this command can be used to assess the human spatial navigation system.

Keywords: Path integration; spatial navigation; vestibular system; visual system

Introduction

Spatial navigation is a crucial everyday skill, which leads to a significant decrease in quality of life when impaired. This complex cognitive skill involves spatial orientation, learning, and memory [1]. At the core of spatial navigation lies the ability to analyze, encode, and retrieve relevant characteristics of the environment, and to use this information to maneuver the body to reach a desired spatial location [2]. Navigation strategies can be categorized as either allocentric or egocentric. Allocentric navigation is reliant upon the recollection of specific landmarks and the capacity to orient oneself relative to a previously recognized object or feature within a given setting [3]. On the other hand, egocentric navigation relies on path integration, which involves continuously updating both the distance and direction traveled from an initial starting point using one's own self as a reference frame [3-5].

Path integration is the ability to use self-motion information generated by one's own body movement to keep track of one's position in space, and is generally described as a mechanism that predominates when visual information is minimized or absent. These self-motion include inputs from the visual, vestibular, and proprioceptive systems. The visual system is responsible for processing visual information generated by either self-movement or environmental changes, resulting in optic flow [6]. This visual information plays a crucial role in avoiding obstacles and, when combined with vestibular signals, helps determine the spatial representation of objects [7, 8]. The somatosensory and proprioceptive systems, on the other hand, provide sensory feedback related to touch, pressure contact, and limb motion from the skin, muscles, joints, and tendons [9]. The vestibular system is responsible for detecting motion of the head and distinguishing between linear accelerations (sensed by the saccule and utricle) and angular accelerations (sensed by the semicircular canals) [10]. Vestibular signals play a significant role in determining both the heading direction and the location of objects. They provide inputs to head direction cells for encoding heading direction and to place cells for encoding object location [11]. For path integration, the estimation of both direction and distance is required. In the absence of visual flow information, angular displacements are estimated primarily based on vestibular information from the semicircular canals, and linear displacements are estimated primarily based on proprioceptive information, but also from information pertaining to linear acceleration transmitted by the otolith organs found in the vestibular labyrinth of the inner ear [12, 13]. As an individual moves along a path in their environment, information about rotations and translations must be integrated continuously in order to calculate their position with respect to the journey's starting point [14]. Thus, when using path integration, external sensory information from the environment such as familiar visual, tactile or olfactory stimuli must be provided occasionally to confirm or update the individual's position and correct for cumulated error [15].

There are studies using various methods to evaluate Path Integration (PI) skills. Some of these studies for evaluating the navigation system currently are Triangle Completion Test [16], Hidden Goal Task [17] Blue Velvet Arena [18], Path Integration Along a Linear Trajectory [19] and variations can be used for navigation evaluations. In addition to these, the "Navigation Test," a vestibular rehabilitation method put forth by Alpini et al., is also at your disposal [20]. These active navigation tests have some practical limitations. We believe that the test we designed is characterized by its simplicity, comprehensibility, and, importantly, enhanced comfort during practical implementation.

PI mechanisms come into play when visual information is limited or absent. In this study, it was aimed to design a path integration test that uses body-based self-motion cues without visual cues. We compared the time to return to the starting point, reference coordinates and foot length of the participants against commands given without visual input in a group of healthy young people. Thus, we disabled the visual system and evaluated the path integration mechanism.

Methods

The study consisted of 157 healthy volunteers, including 86 females and 71 males. The average age was 31.57±13.57 (range 18–70 years). All participants were divided into five different groups in terms of their age 18 to 20 (n=16), 21 to 29 (n=30), 30 to 39 (n=39), 40 to 49 (n=34), and >50 (n=38). Participants with normal hearing (pure tone audiometry<25 dB HL), vestibular and proprioceptive system functions, no dizziness attacks in the last 6 months, and normal physical and mental functions were included in the study. Participants who did not meet these criteria were excluded from the study.

We established a customized area measuring 3×3 meters, equipped with a coordination plane positioned on the ground. This platform featured markings in 5×5 cm2 increments, enabling precise determination of x-y coordinates. Importantly, there was no risk of falling, as the floor was at ground level. We showed the participants the testing room to show that there was no risk of falling or crashing. The participants' movement distances were calculated based on the coordinate plane on the floor. The stopwatch was initiated as they commenced the command and stopped upon its completion. At the conclusion of the command, their location coordinates were analyzed with reference to the heel level for accuracy assessment. To eliminate visual inputs, participants' eyes were covered with a patch throughout the test. The test room was completely soundproofed, ensuring the absence of any external sound sources. To prevent potential sound-based localization cues, the examiner delivered commands to the participant while moving within the test room, thereby varying the source location.

The reference point in the coordinate plane is established as (0,0), which is the intersection of the x and y planes. Before beginning the test, each participant's right foot heel was positioned at the predefined reference starting point on the coordinate floor. On the platform, each participant repeated the proper movement in six different combinations (See Figure 1). To avoid the learning effect, each participant began the test with a unique command set.

Those six command sets are:

1. One step forward, one step forward, turn 90°

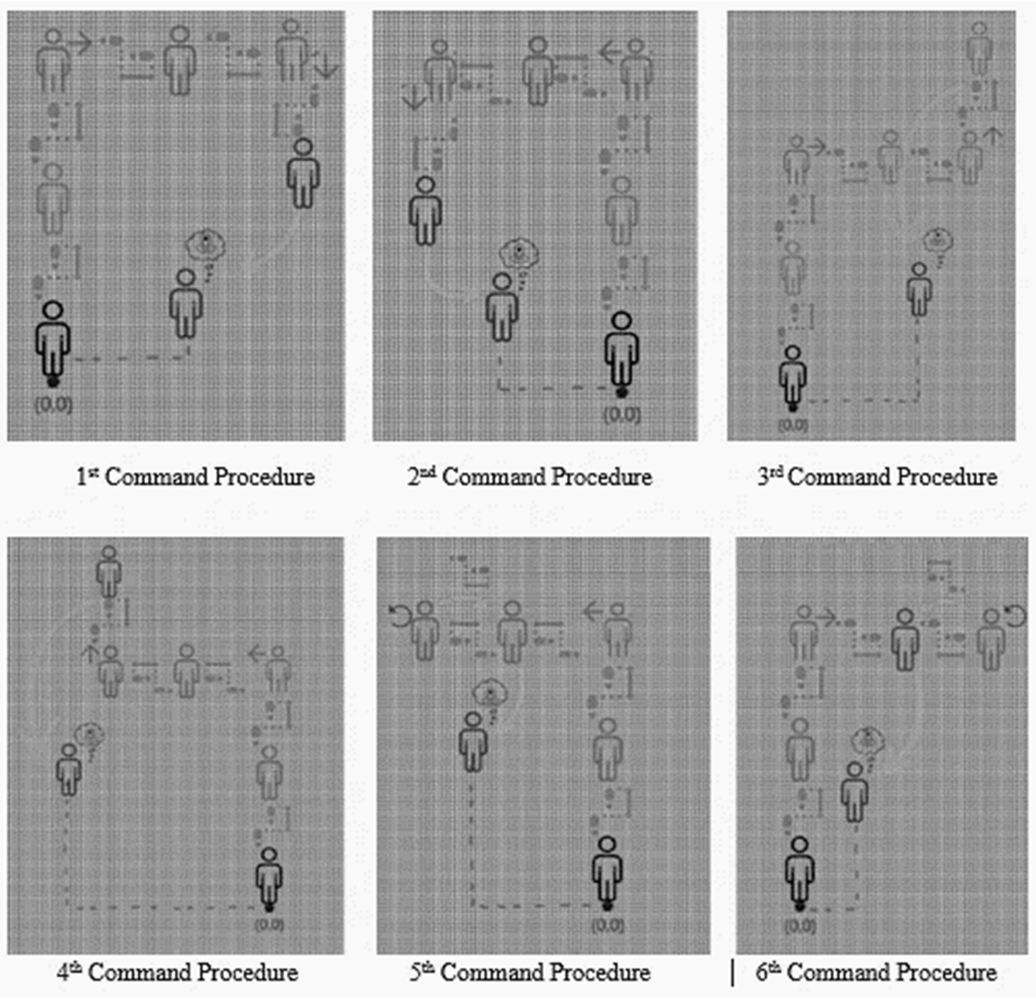

Figure 1. Six different commands given to the participants in order

rightward, one step forward, one step forward, turn 90° rightward, one step forward, return to the starting point from the shortest way.
2. One step forward, one step forward, turn 90° leftward, one step forward, one step forward, turn 90° leftward, one step forward, return to the starting point from the shortest way.
3. One step forward, one step forward, turn 90° rightward, one step forward, one step forward, turn 90° leftward, one step forward, return to the starting point from the shortest way.
4. One step forward, one step forward, turn 90° leftward, one step forward, one step forward, turn 90° rightward, one step forward, return to the starting point from the shortest way.
5. One step forward, one step forward, turn 90° leftward, one step forward, one step forward, turn 180° back, one step forward, return to the starting point from the shortest way.
6. One step forward, one step forward, turn 90° rightward, one step forward, one step forward, turn 180° backward, one step forward, return to the starting point from the shortest way.

Following each command, the time and Euclidean distance were measured. Also, the time to return to the initial position was recorded. The distance between the participants' initial (0,0) and the final positions (the estimated initial position of the participant) was measured in accordance with the x and y planes, as well as the Euclidean distance (z) for the final location was calculated using the x and y values. We identified the second command as having the lowest standard deviation among the six commands. For this reason, we conducted to create norm values with the second command.

Statistical analysis

IBM SPSS Statistics 22.0 package software was used for statistical analysis. Skewness-Kurtosis test was used to determine whether numerical data were normally distributed. Mann Whitney U and Kruskal-Wallis tests were used to compare non-parametric data. Spearman correlation analysis was used in the correlation analysis. For the confidence interval of the second command set, the quarters interval was taken into consideration. The statistical significance value was accepted as $p<0.05$ and the confidence interval was taken as 95%.

Results

Standard deviations calculated according to the Euclidean distance (z), showed that the lowest standard deviation was obtained in the second command set, which was determined to be the most reliable test (Table 1).

Table 2 presents the x, y and z coordinate change values. For the "normalization area" of the second command set, the confidence interval for the x plane (–26.88 to 11.40) and y plane (–16.13 to 32.4) were determined to be normal (Figure 2).

There was no significant difference between the deviation values in the xyz planes of the different age groups in the second test (Table 3) ($p>0.05$). There was a significant difference between the age groups regarding the duration of completion (s) of the second test ($p<0.05$) (Table 4). No significant difference was observed in the comparisons of the deviations in the x and y planes for all commands by gender (Table 5) ($p>0.05$). In the results

Table 1. Euclidean distance of start and end points (z) for all command sets

Command set	Mean	SD
1	43.70	36.75
2	47.51	33.75
3	51.16	36.52
4	51.48	33.78
5	47.17	34.04
6	48.87	36.35

Table 2. Descriptive statistics of command set 2

Reference point distance	Mean	Median	SD	Minimum	Maximum	Percentile 25	Percentile 75
X coordinates	−9.57	−8.00	38.57	−139.00	207.00	−27.00	12.00
Y coordinates	11.59	7.00	41.21	−74.00	173.00	−16.00	33.00
Z coordinates	47.51	40.01	33.75	0.00	207.02	25.50	56.61

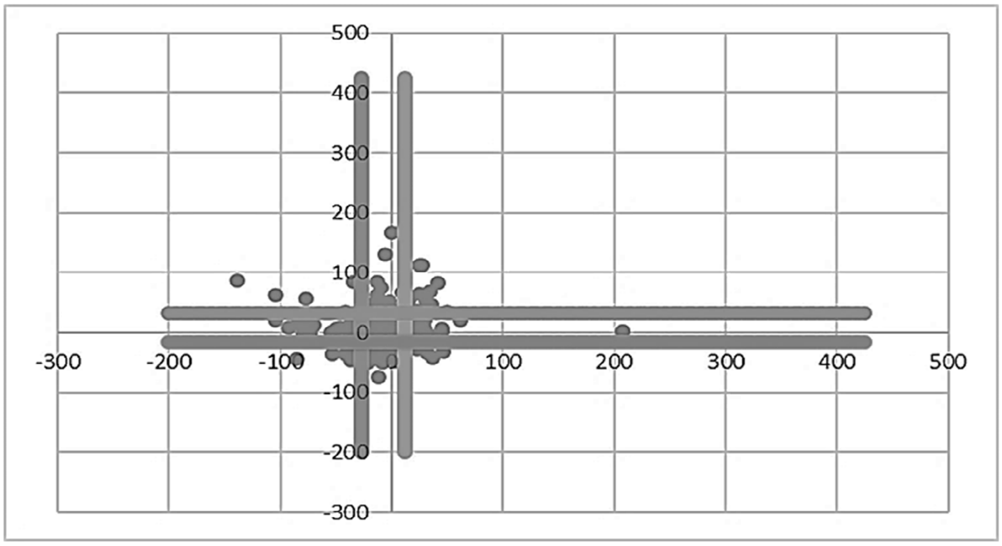

Figure 2. According to the second command, the x, y and z axis values of the participants

Table 3. Comparison of the deviation amounts in the x, y, and z planes according to age groups of the 2nd command set

	Age categories	Minimum	Maximum	Median	p
X plane of 2nd command set (Euclidean distance)	20<=	−139.00	30.00	−11.00	0.786
	21–29	−78.00	25.00	0.50	
	30–39	−104.00	50.00	−12.00	
	40–49	−104.00	207.00	−4.00	
	50+	−93,00	46,00	−8,50	
Y plane of 2nd command set (Euclidean distance)	20<=	−48.00	113.00	−0.50	0.516
	21–29	−39.00	173.00	14.00	
	30–39	−74.00	131.00	7.00	
	40–49	−51.00	84.00	0.00	
	50+	−40.00	74.00	6.00	
Z plane of 2nd command set (Euclidean distance)	20<=	11.40	163.45	38.31	0.997
	21–29	10.63	173.29	38.53	
	30–39	2.00	131.14	37.00	
	40–49	0.00	207.02	40.68	
	50+	2.24	93.34	43.36	

Table 4. Comparison of age groups according to the completion time of the second test

Age categories	Mean	Median	SD	p
20<=	5.91 s	4.15 s	4.32 s	<0.001*
21–29	6.14 s	5.26 s	2.92 s	
30–39	7.65 s	5.90 s	4.74 s	
40–49	6.73 s	6.77 s	2.75 s	
50+	9.61 s	9.34 s	4.23 s	

* p<0.001

Table 5. Comparison of deviations in x and y planes by gender

	Gender	Mean	SD	Median	p
X plane of the 1st test	Male	13.00	35.62	5.00	0.557
	Female	9.86	31.75	2.00	
Y plane of the 1st test	Male	11.01	38.96	2.00	0.867
	Female	12.25	46.75	5.00	
X plane of the 2nd test	Male	–8.47	36.31	–4.00	0.230
	Female	–10.25	40.24	–12.00	
Y plane of the 2nd test	Male	16.47	42.60	7.50	0.135
	Female	7.83	39.64	7.00	
X plane of the 3rd test	Male	22.06	50.13	13.50	0.109
	Female	10.98	34.58	6.00	
Y plane of the 3rd test	Male	20.35	33.23	20.00	0.252
	Female	17.90	46.28	11.50	
X plane of the 4th test	Male	–10.54	48.70	–6.50	0.302
	Female	–0.67	40.68	–4.00	
Y plane of the 4th test	Male	20.96	40.63	16.50	0.757
	Female	19.78	40.30	15.00	
X plane of the 5th test	Male	7.81	40.65	7.50	0.526
	Female	–7.99	42.14	–7.00	
Y plane of the 5th test	Male	11.72	39.66	–1.00	0.777
	Female	10.23	42.53	7.00	
X plane of the 6th test	Male	23.82	46.54	15.50	0.289
	Female	18.30	46.18	5.00	
Y plane of the 6th test	Male	14.25	37.28	12.50	0.449
	Female	3.84	31.71	1.00	

showing the relationship between step length and test parameters, there was a positive correlation between the durations for the first and third tests and footstep lengths ($p<0.05$) ($r=0.193$ and 0.207), while no correlation was found for the other parameters ($p>0.05$).

Discussion

The balance system gets the data from visual, somotosensorial and vestibular systems and processes them for to maintain the center of gravity on the support surface, keeping the gaze fixed during head movements and maintaining the posture of the body. In addition, the balance system also contributes to the regular operation of the spatial orientation and spatial navigation system. Spatial navigation is a fundamental skill that involves cognitive abilities including spatial orientation, memory and learning. These skills require personal (egocentric) and environmental (allocentric) perception. PI is mainly an egocentric navigation strategy and is related to the ability to be used to track one's position in space using body movements. Although the main data sources for the system are vestibular and visual signals, the former play an important role in visual and nonvisual situations for spatial representation [21]. The presence of visual data restriction causes difficulty in performing a spatial navigation task – such as traveling on a known route, especially with people who have peripheral vestibular hypofunction [22].

This study aimed to develop a path integration test that relies solely on body-based self-motion cues, eliminating the reliance on visual cues. Our approach involved crafting a straightforward, user-friendly test floor tailored for clinical applications. Simultaneously, we endeavored to identify the most effective command for path integration assessment.

There are studies using various methods to evaluate PI skills. Some of these studies for evaluating the navigation system currently are Triangle Completion Test [16], Hidden Goal Task [17] Blue Velvet Arena [18], Path Integration Along a Linear Trajectory [19] and variations can be used for navigation evaluations. The spatial navigation tests employed do exhibit some limitations. For instance, the Triangle Completion test, employed in another path integration assessment, presents concern due to substantial variations observed within and between subjects. Furthermore, its reliability and validity have not been definitively established yet. Hidden Goal Task mainly depends on a previously memorized target position, in relation to the starting position (egocentric variant) and/or other navigational landmarks (allocentric variant of the task). We believe that usage of the allocentric strategy may limited to understand the vestibular deficit effects. Similarly, the Blue Velvet Arena test depends on both allocentric and egocentric navigation. Different from these, Path Integration Along a Linear Trajectory mainly depends on egocentric navigation but this test has no turns. The vestibular system is responsible for detecting the motion of the head and angular accelerations. We consider that the patient's turns may cause more specific vestibular stimulation in terms for semicircular canals.

What sets our test apart from others is its remarkable ease of application in clinical settings. Unlike some tests that can be influenced by environmental factors, such as the floor maze test, our test yields reliable results in a wide range of settings, making it highly practical. Notably, it requires minimal resources and can be administered virtually anywhere with ample space. It's worth mentioning that, to the best of our knowledge, there are currently no established norms for PI tests among healthy individuals. Our primary objective has been to establish standardization within this group, paving the way for future studies to facilitate meaningful comparisons with non-healthy cohorts.

In our applied tests, we assessed the standard deviation of the distances across six different trials. This analysis was conducted by considering the Euclidean distance (z) between the starting point and the endpoint of each participant's test run. We hypothesized that a reduction in the standard deviation would enhance the reliability of the test. As indicated in Table 1, we identified the second command as having the lowest standard deviation among the six trials. For this reason, we conducted to create norm values with the second command. Consequently, we established a normalization based on the results of the second command test.

When comparing the deviation amounts of the second test across different age groups, we observed mixed results. We suspect that the variation in participant numbers among these groups might contribute to this disparity in outcomes. Furthermore, despite providing each individual with practice sessions before the tests, it's important to note that some participants encountered challenges in grasping and executing the test effectively. While the participants in our study are generally mentally and physically healthy, it's essential to acknowledge that individual differences can still play a role and potentially influence the test results. As age increases, we observed that the completion time of the second test also tends to increase. This phenomenon could be attributed to the natural slowing down of mobility and executive functions that often accompany the aging process. Nevertheless, we believe that this test can still be readily employed within the elderly population, as it doesn't demand excessive physical or cognitive effort.

There are variable results in navigation studies conducted by gender. Even though some studies have found that men perform better than women, most researchers have found no gender-based differences in spatial navigation [23, 24]. In our results, no difference was observed between men and women. Likewise, the fact that our participants consisted of completely healthy people may have been effective.

The role of cognitive skills in path integration should not be underestimated. There is an established link between cognitive impairment and a decline in spatial navigation skills. Older adults demonstrate reduced allocentric abilities, difficulty switching between spatial navigation techniques and deterioration in spatial memory [25-27]. In our study, we did not thoroughly assess cognitive skills, which is an area that warrants more comprehensive examination in future research. This includes a detailed evaluation of cognitive abilities such as executive functions, working memory capacity, and attention. It's worth noting that our study had uneven sample sizes across age groups, with a larger representation of younger participants. In future research, may aim for a more balanced distribution of participants to ensure statistical robustness. Additionally, it's important to highlight that our study primarily focused on establishing normative values using a healthy population. In forthcoming studies, may expand the application of this test to more specific patient groups to explore its utility in clinical contexts. For example, the effects of spatial navigation skills in neurological diseases such as Alzheimer's and Dementia can be evaluated. Additionally, this test can be applied to groups with vestibular pathology and compared with normal group values.

Conclusion

The creation of a normative confidence interval based on the 2nd test with the lowest standard deviation is a sensible approach for establishing a reference range in your study with healthy individuals. Furthermore, your findings indicating that the time to complete the test increases with age among these healthy participants, suggesting a decline in navigation skills with advancing age, is a noteworthy observation. It provides valuable insights into the relationship between age and navigation abilities.

Limitations

Our study had a relatively limited sample size. The examination of test commands could benefit from a more extensive participant pool. Additionally, we did not conduct an exhaustive assessment of cognitive abilities, including a comprehensive evaluation of executive functions, working memory capacity, and attention. Future research endeavors should consider a thorough examination of these cognitive skills.

Ethical Considerations

Compliance with ethical guidelines

The study was approved by the Ethics Committee of Non-Interventional Clinical Research (decision no: 298, date: 29.03.2019). Written informed consent was obtained from all participants.

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Authors' contributions

OY: Study design, interpretation of the results, statistical analysis and critical revision of the manuscript; CK: Study design, acquisition of data, and drafting the manuscript; KE: Study design, acquisition of data, interpretation of the results; OG: Interpretation of the results and critical revision of the manuscript; SE: Statistical analysis and interpretation of the results; MBS: Interpretation of the results and critical revision of the manuscript.

Conflict of interest

The authors have no conflicts of interest to disclose.

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