



Locomotion toward a Perceived Target in Virtual Reality: Effect of Incompatibility between Visual and Vestibular Information

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Abstract

To successfully move toward a goal, humans construct and update internal representations based on sensory information about their movement. This intricate process heavily relies on internal cues, particularly optic flow, the pattern of motion on the retina, as well as rotational and linear acceleration information obtained through the vestibular system. In addition to these internal cues, humans utilize external cues to understand the external world, thereby enabling more accurate navigation behaviors.

This study investigated the utilization of internal cues in updating internal representations and explored the possible role of external cues when inconsistency arises among these internal cues. In this study, participants were engaged in a target-oriented walking task covering a distance of 5 meters in a virtual reality environment. A total of 10 experimental conditions were created based on three factors: head directions (0°, left 30°, right 30°), prism rotations (no prism, left 30°, right 30°), and the presence or absence of visual information. First, an analysis was conducted to assess the impact of these factors on overall movement parameters and walking trajectories. Next, comparisons were made between walking trajectories when visual cues and vestibular cues were consistent or inconsistent.

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The findings of this study revealed a significant effect of prism rotation on walking distance, time, speed, and lateral deviation in trajectory, suggesting that inconsistency between vestibular and visual cues leads to different walking patterns than when the two cues align. Furthermore, the results showed that neither cue dominated over the other when the cues were incompatible. Instead, there is a possible influence of an external visual cue, particularly the perceived location of the target.

These findings were expected to contribute to the research on the utilization of sensory information in spatial perception. Moreover, this study was anticipated to lead to future research on helping spatial perception in patients who have difficulty integrating sensory information to build an internal representation and research on reducing the problem of cybersickness in virtual reality due to sensory discrepancies.

Keyword: target-oriented locomotion, virtual reality, prism rotation, optic flow, vestibular information, perceived target

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Chapter 1. Introduction

1.1. Internal representation for goal-directed locomotion

To move toward a desired goal, humans constantly use internal representations of the body and space to locate and steer their movements. According to Cardinali et al. (2009), who divided the internal representation into body and spatial information, it can be categorized into two concepts: body schema and peripersonal space. First, body schema is the understanding of the body's position, shape, and dimensions (Cardinali et al., 2009; de Vignemont, 2010; Ivaneko et al., 2011). Initially introduced by Pierre Bonnier (1905) as "an organized spatial representation or spatial sense of body," the notion of body schema was refined by Head & Homes (1911–1912) into the concept of postural schema, which is used in its most common sense (Cardinali et al., 2009). In essence, body schema conceptualizes the body in terms of space, which is further used as a concept of action.

Next, the internal representation of space can be divided into peripersonal space and extrapersonal space based on their respective relation to the body. Specifically, peripersonal space refers to areas that can be reached by stretching out a body part, while areas beyond

that require locomotion of the body and are typically defined as extrapersonal space (Rizzolatti et al., 1997; Previc, 1998; Holmes & Spence, 2004). In other words, internal representations of space are inherently associated with movement in a space (Cardinali et al., 2009). With these conceptual definitions, body schema, peripersonal space, and extrapersonal space were considered body and spatial internal representations of movement, respectively.

Not only do the two internal representations have movement as a common goal, but they also utilize movement as a common means. Within the central nervous system, motor commands are computed based on the understanding of the body to achieve its purpose (the inverse model). Simultaneously, movements are executed with anticipation of the sensory consequences that will be generated (the forward dynamic model). Significantly, information about a space, including objects and the environment, acquired through the sensory inputs, updates the motor commands (the forward sensory model) (Wolpert & Ghahramani, 2000). Given this relationship between the understanding of the body and that of space, these two representations can be viewed as a unified internal representation.

Based on previous studies that have compared body schema to various related concepts such as body image, body structural description, visuospatial body map, and body semantics (Cole & Pillard,

1995; Gallagher & Cole, 1995), de Vignemont (2010) notably defined body schema as a sensorimotor representation. The process of integrating sensory inputs and motor outputs to generate and maintain internal estimations of the external environment and one's own body is called sensorimotor integration, with the superior parietal lobe playing a critical role in this process (Wolpert et al., 1998). The superior parietal lobe is also associated with the dorsal pathway, known as the vision for action pathway (Milner & Goodale, 2006). Based on this evidence, the body schema can be regarded as an internal representation formed by sensorimotor information.

The notion of internal representation extends to spatial representations of movement. In a functional magnetic resonance image (fMRI) study examining achondroplastic dwarfs who received about 15 cm leg extensions for 6 months, the researchers investigated whether changes in internal body representation were evident in specific brain regions (Di Russo et al., 2006). The results revealed the involvement of the superior parietal lobe in encoding relationships between the body parts and between the body and the environment (Di Russo et al., 2006; Cardinali et al., 2009). These results imply that the superior parietal lobe contributes to body and spatial representations, suggesting a potential integration of the two representations within the concept of internal representation, in which the superior parietal lobe

plays a vital role. Notably, peripersonal space exhibits a solid connection to internal representation compared to extrapersonal space. Neurologically, the distinction between peripersonal and extrapersonal space has also been elucidated by the involvement of the frontal-parietal network in peripersonal space (Cardinali et al., 2009) and the predominance of the ventral pathway (Bjoertomt et al., 2002) in peripersonal space (Iachini et al., 2014). Therefore, peripersonal space can be integrated into internal representations in addition to body schema.

1.2. Internal representation based on sensory cues

For more accurate movements, humans build a more accurate internal representation based on sensory information (Ernst & Bulthoff, 2004). During bodily locomotion, various sensory inputs are utilized, including proprioceptive information from receptors in muscles and joints, afferent information concerning motor commands to muscles, visual information about patterns of movement on the retina, and vestibular information about detected linear or rotational acceleration through the semicircular canals and otoliths (Berthoz, 2000; Ivaneko et al., 1997; Cheng et al., 2007).

First, optic flow is visual information on the retina about the patterns of motion that occur during bodily locomotion. It serves as a visual cue for movement and allows humans to determine their direction, i.e., information about one's movement (Gibson, 1950; Harris et al., 2000; Warren et al., 2001; Frenz & Lappe, 2005). In addition, optic flow provides humans with spatial information about their location. Precisely, humans can determine the distance and contact time between themselves and a target or an obstacle, which allows humans to plan appropriate movement behaviors such as locomotion and avoidance (Frenz & Lappe, 2005).

To explain the reliance on optic flow movement, numerous studies have proposed optic flow theory (Rushton et al., 1998; Warren et al., 2001). According to this theory, humans use optic flow to compensate for discrepancies between the perceived direction and target location, moving the focus of expansion to align it with the target (Warren et al., 2001). These studies manipulated the participants' optic flow, often through prism glasses, while participants were walking toward a target. The results showed that movement trajectories were indeed influenced by optic flow, thereby suggesting the impact of optic flow on the locomotion process (Warren & Hannon, 1988; Royden et al., 1992; van den Berg, 1993; Warren et al., 2001). In light of these findings, a further question can be asked: Is optic flow critical in

shaping our internal representations of the body and space?

In contrast, there are some studies that argue against this view. They suggest that vestibular information plays a more prominent role than visual information (Kennedy et al., 2003; Harris et al., 2000; Telford et al., 1995). For instance, in a study that manipulated visual and vestibular information through prism glasses and a vestibular stimulation device, the researchers observed greater lateral deviations in trajectory under vestibular stimulation conditions than visual manipulation conditions (Kennedy et al., 2003). Furthermore, adding visual cues to vestibular cues did not vield significant performance improvements (Telford et al., 1995), and participants reported vestibular cues as more helpful information in predicting their movements than visual cues (Harris et al., 2000). These findings raise another question: Is vestibular cue more critical in shaping internal representations of the body and space?

However, contrasting studies have highlighted the importance of both visual and vestibular cues. Carlsen et al. (2005) conducted an experiment involving goal-directed walking and observed an additive effect when manipulating sensory information using a combination of vestibular stimulation devices and prism glasses. The simultaneous use of these two sensory manipulations resulted in more significant trajectory deviations than either sensory manipulation alone (Carlsen et al., 2005). Furthermore, Berger & Bulthoff (2009) conducted a study exploring participants' attention during a mismatch between visual and non-visual cues. The findings indicated that participants could selectively attend to visual or non-visual cues while disregarding the other to return to their initial positions (Berger & Bulthoff, 2009). Hence, while ongoing debates persist regarding the relative importance of sensory cues for movement, it is evident that both visual and vestibular cues contribute to the process of locomotion toward a goal.

1.3. Internal representation and external cues

In addition to internal representations of movement, external cues pertaining to the external environment play a significant role. As discussed by Arleo & Rondi-Reig (2007), humans receive sensory information classified into two categories: idiothetic and allothetic cues. Idiothetic cues encompass self-motion-related information, including optic flow, vestibular signals, proprioceptive information, and afferent information. On the other hand, allothetic cues offer insights into the external environment and come as visual, olfactory, auditory, and somatosensory information. Since idiothetic cues are information about self-motion and allothetic cues are information about the external environment, these terms can be regarded as indicative of internal cues and external cues, respectively. While external cues offer static information about space, internal cues provide dynamic information generated through movement (Arleo & Rondi-Reig, 2007). In addition to updating internal representations based on internal cues to facilitate accurate goal-directed movement, humans rely on external cues to develop their understanding of the external world. Consequently, both internal cues and external cues are essential components of spatial perception for moving to a designated goal.

Following the notion that both types of cues are involved in spatial perception and the locomotion process, it becomes crucial to explore how humans use both cues in navigation. In a study investigating the utilization of external spatial cues (landmark cues) and non-visual internal information about movement (vestibular cues and proprioceptive cues) among children and adults, the researchers observed distinct strategies employed by the two groups. Adults primarily employed an integration method, eventually leading to accurate navigation, whereas children relied on an alternation method, resulting in inaccurate navigation (Nardini et al., 2008). It is evident that a more accurate spatial perception can be obtained by using both internal movement cues and external spatial cues.

To understand the involvement of the two types of cues in locomotion, a Bayesian framework can provide insights into their relationship. According to a Bayesian perspective that elucidates human locomotion, sensory cues related to movement can be explained by applying a Bayesian prior (Cheng et al., 2007). More specifically, in a study investigating the impact of vestibular information on the perception of passive body movement, participants perceived that they were moving in the direction they were facing, which is a Bayesian prior (Ivaneko et al., 1997). In essence, individuals formed a belief about movement based on sensory information about movement, which is internal representation. This internal representation was further updated by integrating the probability of newly received sensory cues. It is important to note that these sensory cues were not limited to internal cues (e.g., optic flow) but included external cues, such as landmarks and other objects present within a navigating space (Cheng et al., 2007).

1.4. Significance and purpose of the study

As Ernest & Bulthoff (2004) suggested that integrating two sensory cues yields a more robust perception with less variability and higher reliability than relying on a single sensory cue alone, the belief or internal representation becomes stronger when multiple sensory cues are available. Nevertheless, it is essential to consider that internal cues may not always give us the same information, and a mismatch between the cues can influence our belief.

Previous studies have examined sensory mismatch conditions and their impact on movement patterns and spatial perception. Lee & Aronson (1974) found that visual information is more dominant when there is a mismatch between visual and non-visual information about movement, especially in children who are still developing muscle control. However, it is important to note that the study focused on standing rather than locomotion. Walking, which involves moving to a specific location while maintaining a standing position, requires processing more complex and various information; thus, a more accurate perception of space and self-motion is expected (Waller et al., 2004). Nevertheless, most of the studies comparing visual and vestibular information for movement used a vestibular stimulation device to induce manipulated head rotation or sway (Kennedy et al., 2003; Carlsen et al., 2005) and often rotated the body while participants were sitting instead of direct body locomotion (Harris et al., 2000; Telford et al., 1995; Berger & Bulthoff, 2009).

These approaches cannot provide other non-visual movementrelated information, such as proprioceptive and afferent input, that can

be acquired through actual body movement. Furthermore, they do not encompass voluntary movements of participants. Consequently, it is hard to say that these studies fully capture the intricacies of targetoriented locomotion based on direct head rotation and body locomotion. Similarly, according to Nardini (2021) that investigated the effect of a viewpoint change on spatial perception, participants did not walk to the target location, but only a viewpoint changed; thus, their spatial perception became inaccurate (Nardini et al., 2006; Negen et al., 2018). To comprehensively explore the concept of the multisensory internal representation of movement, it is crucial to investigate tasks involving body locomotion, such as walking, and voluntary movement, such as head rotation.

Although the sensory information mismatch may not commonly occur in daily life, it is not only caused by experimental manipulations. Brain damage can also lead to difficulties in constructing internal representations. Specifically, patients with unilateral visual neglect exhibit veering, taking a different course when navigating toward a target (Shillcock et al., 1998; Rushton et al., 1998). Karnath (1994) posited that patients with unilateral visual neglect struggle with integrating vestibular and proprioceptive inputs to compute egocentric or body-centered coordinates. Rushton et al. (1998) further underscored that the patients with unilateral visual neglect encounter

difficulties in recognizing external visual cues based on the body. Thus, it can be inferred that patients with unilateral visual neglect have difficulty utilizing internal and external cues due to an incomplete internal representation, leading to deviations in their movement trajectories. This interpretation highlights the significance of understanding the spatial perception of patients who have difficulty building internal representations and underscores the need to explore the relationship between internal and external cues for rehabilitation purposes.

Furthermore, another domain where sensory information conflict in spatial perception is emphasized is the problem of cybersickness due to sensory information discrepancies in virtual reality. According to sensory conflict theory, cybersickness emerges due to a conflict between sensory input signals about movement, including visual and vestibular (Ng et al., 2020; Reason & Brand, 1975; Claremont, 1931). Since unpleasant initial experiences with virtual reality are known to discourage subsequent attempts, it is necessary for ongoing research endeavors to aim at mitigating cybersickness within the virtual reality domain (Jerald, 2015; Cao et al., 2018). A study examining the induction of vestibular-visual mismatch by rotating visual information in a virtual reality space at an angle twice as large as the angle at which the head was rotated and measured motion sickness (Akiduki et al., 2003) found both subjective motion sickness and objective postural instability of participants and identified a temporal discrepancy between the onset of motion sickness and postural instability. These findings suggest that sensory information conflict hampers the maintenance of an accurate internal representation of the body, leading to motion sickness and subsequent postural instability (Akiduki et al., 2003). Thus, to address the problems faced by the virtual reality industry, it is essential to investigate situations involving sensory information conflict within virtual reality environments and establish connections with research to reduce cybersickness.

The present study included experimental conditions involving participants voluntarily rotating their heads and conditions where visual information was manipulated using prism rotation. These conditions aimed to create situations where the vestibular and visual information about movement were compatible or incompatible. After participants walked directly toward a target in this environment, their locomotion trajectories were analyzed to investigate the cues they relied upon to navigate. The findings of the current study hold potential applications in spatial perception rehabilitation for patients experiencing difficulties in integrating sensory cues and in solution for the issue of cybersickness in virtual reality, which arises from discrepancies in sensory information about movement.

Chapter 2. Methods

2.1. Participants

A total of 21 healthy adults (12 males, 9 females, mean age = 25.33 \pm 0.64, age range: 21-35) with normal visual acuity participated in this study. All participants were recruited from Seoul National University and gave written informed consent before participating. Based on the analysis of the kinematic features in the baseline condition, 2 subjects who performed poorly were excluded from data analysis, resulting in 19 subjects for analysis.

2.2. Apparatus

The Unity 3D (Version 2019.3f1, Unity Technologies, USA) program was utilized to create the HMD-VR experimental environment. Four SteamVR Base Stations 2.0 (HTC, Taiwan) were attached to the four top corners of the experiment room and used to keep track of the virtual reality equipment. Within this environment, participants used a VIVE Pro Eye Head Mounted Display (HTC, Taiwan), offering a field of view of 110° and a per-eye resolution of 1,440 × 1,600 pixels. During the experiment, participants wore the HMD on their heads,

allowing real-time collection of head positions (**Figure 1a**). To collect data regarding body positions, three VIVE Trackers (HTC, Taiwan) were employed. These trackers measured the real-time positions of body parts, including the back and both feet, to calculate the angle between the head and the back and to visualize the feet while participants participated. Before starting the experimental task, participants were outfitted with a chest harness to ensure proper posture and provided with indoor shoes that corresponded to their shoe sizes. The tracker for the back was attached to the back side of the chest harness, while the foot trackers were attached to the indoor shoes (**Figure 1b** and **1c**). Retractable belt barriers were placed around the experiment room to enable participants to walk safely.



Figure 1. Virtual reality tracking devices. (a) a Head Mounted Display on the head. (b) a tracker on the back. (c) two trackers on the feet.

2.3. Procedure

Before participation, each participant provided his or her demographic information, such as age and gender, along with shoe size. After participants were fully equipped with the provided experimental equipment, they performed all subsequent procedures in the HMD-VR experimental environment, as shown in **Figure 2**. First, participants stood at a starting line, more specifically, placing their feet in between a starting point, which was placed below the starting line. A yellow box appeared as a target at a distance of 6 meters from the starting line in the environment. Under the same verbal instruction provided in all experiment conditions, "Walk to where you think the target is located," participants walked a distance of 5 meters for 10 trials per condition in an indoor experimental space.



Figure 2. Virtual reality experimental environment. (a) The virtual reality scene shown in a Head Mounted Display when a subject stands on the starting point and faces toward a target. (b) a 5-meters walking task toward a target.

A total of 10 conditions was created based on the head rotation and visual manipulation and given in a randomized order for each participant. The conditions include a natural walking condition, walking with a head rotation, walking while visual information was manipulated, walking with a visual rotation and a head rotation, and walking with a head rotation and closed eyes, as shown in **Table 1** and **Figure 3**. The head rotation required the angle between the head and the back to be 0°, right 30°, or left 30°. The visual manipulation was created by rotating the visual field and optic flow as well for 30° to the right or left. For each trial of each condition, participants were required to adjust their body postures accordingly prior to walking. To aid adjustment, the angle between the back of the body and the environment and the angle between the head and back of the body were calculated and presented in real-time to participants in the display. Once the body postures met the required angles, participants were informed to begin walking.

Table 1. Experimental conditions. For head rotation, the head was rotated relative to the body direction. For prism rotation, the visual field displayed via the HMD is rotated. Vision indicates the presence or absence of visual information, determined by whether the participant's eyes are open or closed.

Condition	Head Rotation (°)	Prism Rotation (°)	Vision
1	0	None	On
2	Left 30	None	On
3	Right 30	None	On
4	0	Left 30	On
5	0	Right 30	On
6	Left 30	Right 30	On
7	Right 30	Left 30	On
8	0	None	Off
9	Left 30	None	Off
10	Right 30	None	Off





Figure 3. Expected and actual scene based on condition. HR and PR indicate head rotation and prism rotation. + and - indicate right and left. The actual scenes differed from the scenes expected based on head directions in condition 4, 5, 6, 7. Condition 8, 9, 10 have the same head directions as condition 1, 2, 3 but without visual information.

2.4. Data Analysis

For overall data analysis, a Python-based software called Spyder (Version 5.4.1, Spyder project contributors) was used. Data preprocessing, such as smoothing, normalizing, and interpolating, was performed before data analysis. The position values of the HMD (Head-Mounted Display) were measured at a sampling rate of 90 Hz and went through low-pass filtering with a cut-off frequency of 10 Hz. The real-time position values of the HMD were utilized to obtain a walking trajectory of each trial.

The first trial for each condition of the subjects was not included in the overall data analysis. Based on the trial with the most data points in each condition, the other trials were interpolated so that all trials within the same condition had the same data points. Data point values were averaged within the conditions to compute each participant's average trajectory per condition. Thus, the average trajectory was then used as the representative trajectory for each condition for each subject.

The overall movement parameters were calculated, including the movement time, distance, and average speed for each trajectory. The movement time was defined as the time between a scene change from the posture adjustment to the experimental environment and the

arrival of the HMD at the end line. The movement distance was calculated as the sum of the changes in the x and y coordinates of each HMD position. The average movement speed was calculated using the movement time and distance of each trajectory. Any subjects whose movement parameter values deviated more than 2 standard deviations from the mean in Condition 1 were excluded from data analysis.

In each trajectory, the lateral deviation of each datapoint was calculated as a distance in the x-axis of each HMD position from x = 0. The maximum lateral deviation was obtained by finding the HMD position with the greatest absolute value of a distance in the x-axis from x = 0 while the mean lateral deviation was obtained by averaging the lateral deviations. Each trajectory of 5 meters was divided into five phases of 1 meter each to compare the maximum and mean lateral deviation between conditions. The maximum lateral deviation was expected to reflect the effect caused by the experimental factors, while the mean lateral deviation was expected to show the overall trajectory pattern.

During statistical analysis, Spyder (Version 5.4.1, Spyder project contributors) was used. To analyze the factors of head direction, prism rotation, and the presence of visual information on the overall kinematic features and the lateral deviations, Friedman tests and oneway repeated-measures ANOVAs were used, respectively. To investigate the phase factor on the lateral deviations, one-way repeated measures ANOVA was used. For comparison between conditions, one-way repeated measures ANOVAs and paired-samples t-tests were used, depending on the number of conditions being compared. Post-hoc tests with the Bonferroni method were involved for further analysis of statistically significant results. Any results with p-values less than 0.05 were considered statistically significant.

For data visualization, the number of data points for each trajectory per condition was compared, and the second interpolation based on the trajectory with the most data points was carried out. By averaging the interpolated trajectories within each condition, the overall trajectory per condition for all subjects was obtained. The visualizations were performed by using RStudio (Version 1.3, RStudio, PBC, USA).

Chapter 3. Results

In this study, the movement trajectories were assumed to reflect an internal representation of one's movement when walking 5 meters toward a target in a virtual reality environment. First, the overall movement parameters, including the movement distance, the movement time, and the average movement speed, were shown in **Table 2**. Next, the average maximum and mean lateral deviation of each of the five phases for all conditions were presented in **Table 3** and **Table 4**, respectively. Lastly, the average trajectory by condition was visualized and depicted in **Figure 4**.

Table 2. Average movement parameters. Mean ± SEM for Movement Distance (m), Movement Time (s), and Average Movement Speed (m/s).

Condition	Distance	Time	Average Speed	
1	5.114 ± 0.043	8.465 ± 0.673	0.653 ± 0.038	
2	5.242 ± 0.049	9.588 ± 1.024	0.627 ± 0.047	
3	5.236 ± 0.053	8.663 ± 0.421	0.629 ± 0.028	
4	5.473 ± 0.126	18.433 ± 5.258	0.445 ± 0.045	
5	5.261 ± 0.052	10.762 ± 0.966	0.547 ± 0.040	
6	5.354 ± 0.070	12.922 ± 1.673	0.533 ± 0.054	
7	5.385 ± 0.117	10.315 ± 1.038	0.591 ± 0.044	
8	5.278 ± 0.043	14.594 ± 1.803	0.427 ± 0.032	
9	5.486 ± 0.111	15.253 ± 1.800	0.420 ± 0.034	
10	5.421 ± 0.083	13.397 ± 1.589	0.461 ± 0.032	

Condition	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
1	0.001 ± 0.016	0.005 ± 0.018	0.008 ± 0.021	0.011 ± 0.022	0.005 ± 0.022
2	-0.015 ± 0.035	0.010 ± 0.044	0.019 ± 0.053	0.003 ± 0.059	-0.011 ± 0.062
3	0.075 ± 0.020	0.079 ± 0.032	0.102 ± 0.040	0.119 ± 0.045	0.111 ± 0.050
4	0.211 ± 0.042	0.306 ± 0.059	0.358 ± 0.066	0.371 ± 0.067	0.346 ± 0.064
5	-0.090 ± 0.035	-0.126 ± 0.059	-0.138 ± 0.061	-0.148 ± 0.070	-0.133 ± 0.075
6	-0.151 ± 0.043	-0.207 ± 0.061	-0.221 ± 0.074	-0.226 ± 0.082	-0.214 ± 0.082
7	0.199 ± 0.038	0.273 ± 0.057	0.295 ± 0.071	0.297 ± 0.079	0.251 ± 0.084
8	0.004 ± 0.026	0.016 ± 0.034	0.026 ± 0.044	0.027 ± 0.057	0.027 ± 0.068
9	0.071 ± 0.040	0.139 ± 0.058	0.190 ± 0.075	0.219 ± 0.089	0.233 ± 0.098
10	0.044 ± 0.038	0.054 ± 0.053	0.075 ± 0.067	0.099 ± 0.080	0.110 ± 0.088

Table 3. Average maximum lateral deviation. Mean \pm SEM (m).

Table 4. Average mean lateral deviation. Mean \pm SEM (m).

Condition	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
1	0.001 ± 0.011	0.005 ± 0.015	0.009 ± 0.018	0.011 ± 0.019	0.006 ± 0.019
2	-0.019 ± 0.026	0.009 ± 0.039	0.019 ± 0.049	0.008 ± 0.055	-0.012 ± 0.057
3	0.048 ± 0.013	0.062 ± 0.026	0.085 ± 0.036	0.106 ± 0.042	0.105 ± 0.045
4	0.116 ± 0.024	0.261 ± 0.052	0.332 ± 0.064	0.349 ± 0.065	0.309 ± 0.061
5	-0.060 ± 0.023	-0.110 ± 0.041	-0.128 ± 0.056	-0.136 ± 0.065	-0.122 ± 0.068
6	-0.098 ± 0.029	-0.177 ± 0.053	-0.208 ± 0.068	-0.219 ± 0.076	-0.202 ± 0.076
7	0.119 ± 0.023	0.232 ± 0.049	0.272 ± 0.066	0.276 ± 0.075	0.237 ± 0.077
8	0.001 ± 0.019	0.011 ± 0.029	0.021 ± 0.039	0.025 ± 0.050	0.024 ± 0.063
9	0.038 ± 0.028	0.110 ± 0.048	0.166 ± 0.066	0.204 ± 0.082	0.216 ± 0.093
10	0.041 ± 0.027	0.048 ± 0.045	0.066 ± 0.060	0.088 ± 0.074	0.096 ± 0.083





(b)



(c)

Figure 4. Average trajectory per condition. (a) Condition 1, 2, 3. (b) Condition 4, 5, 6, 7. (c) Condition 8, 9, 10. Black, green, purple, and blue indicate 0°, right 30°, left 30° prism rotation, and no visual information. A filled circle, an empty triangle, and an empty square indicate 0°, left 30°, and right 30° head rotation, respectively. The red dashed line represents x = 0.

3.1. The effect of head rotation, prism rotation, and absence of visual information on overall locomotion

To find the impact of head rotation, prism rotation, and the absence of visual information on movement distance, movement time, and average speed, the Friedman tests were performed. As a result, there were no significant differences based on head rotation and prism rotation while significant differences were found depending on the presence or absence of visual information [movement distance: $\chi^2(1) = 4.263$, p = 0.039; movement time: $\chi^2(1) = 8.895$, p = 0.003; average speed: $\chi^2(1) = 11.842$, p = 0.001] (**Table 5**). However, low Kendall's W values, much less than the small effect indicator suggested by Cohen interpretation guidelines (Cohen, 1988; 1992), were observed for both head rotation and prism rotation.

To consider the statistically significant results and the low effect sizes, the Conover test with the Bonferroni correction method as a post-hoc test was conducted. As a result, no significant differences were found in overall movement based on head rotation. Nevertheless, significant differences were discovered in overall movement between no prism rotation and left [movement distance: *corrected* p = 0.000; movement time: *corrected* p = 0.000; movement speed: *corrected* p =0.000] or right prism rotation [movement distance: *corrected* p =0.000; movement time: *corrected* p = 0.000; movement speed: *corrected* p = 0.000] while there were no differences between right and left prism rotation [movement distance: *corrected* p = 0.818; movement time: *corrected* p = 0.995; movement speed: *corrected* p = 0.890]. Moreover, there were differences between the presence and absence of visual information in movement distance and average speed but not in movement time [movement distance: *corrected* p = 0.014; movement time: *corrected* p = 0.150; movement speed: *corrected* p = 0.014; 0.000] (**Table 6**).

Overall, the presence of prism rotation had a significant effect on overall movements, such as longer distance, longer time, and slower speed [$M_{distance} = 5.368 \pm 0.027$, $M_{time} = 13.108 \pm 0.699$, $M_{speed} = 0.529 \pm 0.014$], compared to the absence of prism rotation [$M_{distance} = 5.296 \pm 0.026$, $M_{time} = 11.660 \pm 0.679$, $M_{speed} = 0.536 \pm 0.014$]. Furthermore, having visual information or not had a significant effect on movement distance and average speed. The presence of visual information led to shorter distance and faster speed [$M_{distance} = 5.295 \pm 0.027$, $M_{time} =$ 11.307 ± 0.690 , $M_{speed} = 0.575 \pm 0.014$], compared to the absence of visual information [$M_{distance} = 5.395 \pm 0.027$, $M_{time} = 14.415 \pm 0.700$, $M_{speed} = 0.436 \pm 0.014$] (**Table 2** and **6**). Table 5. The Friedman test for movement parameters. χ^2 indicates the chi-squared test statistic, *p* indicates the p-value, and *W* indicates the Kendall's coefficient of concordance, which is also known as Kendall's W.

	Head Rotation			Prism Rotation			Visual Info.		
	χ^2	р	W	χ^2	р	W	χ^2	р	W
Movement Distance	3.263	0.196	0.086	1.684	0.431	0.044	4.263	0.039	0.224
Movement Time	2.000	0.368	0.053	0.316	0.854	0.008	8.895	0.003	0.468
Average Speed	2.947	0.229	0.078	0.316	0.854	0.008	11.842	0.001	0.623

Table 6. The post-hoc test for movement parameters. Cor. p

represents corrected p-value.

	Hea	ad Rot	tation	Pris	sm Ro	otation	ation Visual		
	Cont	trast	cor. p	Contrast		cor. p	Cont	rast	cor. p
Morromont	0	L30	0.848	None	L30	0.000	On	Off	0.014
Distance	0	R30	0.848	None	R30	0.000			
Distance	L30	R30	0.854	L30	R30	0.818			
Movement	0	L30	0.356	None	L30	0.000	On	Off	0.150
Time	0	R30	0.328	None	R30	0.000			
Time	L30	R30	0.662	L30	R30	0.995			
Average	0	L30	0.645	None	L30	0.000	On	Off	0.000
	0	R30	0.645	None	R30	0.000			
Speed	L30	R30	0.645	L30	R30	0.890			

3.2. The effect of head rotation, prism rotation, and absence of visual information on trajectory pattern

To examine the effect of head rotation, prism rotation, and the presence of visual information on movement error, including the maximum and mean lateral deviations, the one-way repeatedmeasures ANOVAs were used. As a result, there were significant differences discovered in lateral deviations depending on head rotation [max: F(2, 36) = 3.483, p = 0.041; mean: F(2, 36) = 3.415, p = 0.044] and prism rotation [max: F(2, 36) = 20.365, p = 0.000; mean: F(2, 36) = 20.332, p = 0.000] while there were no differences between the presence and absence of visual information [max: F(1, 18) = 1.820, p = 0.194; mean: F(1, 18) = 1.915, p = 0.183] (**Table 7**).

Post-Hoc tests using the Bonferroni method were carried out for further analysis. The results showed that there were significant differences between no, left, and right prism rotation in max lateral deviation [none and left 30: t(18) = 4.822, corrected p = 0.000; none and right 30: t(18) = 3.881, corrected p = 0.003; left 30 and right 30: t(18) = 4.645, corrected p = 0.001] and mean lateral deviation [none and left 30: t(18) = 4.758, corrected p = 0.000; none and right 30: t(18)= 3.910, corrected p = 0.003; left 30 and right 30: t(18)= 3.910, corrected p = 0.003; left 30 and right 30: t(18) = 4.646, corrected p = 0.001] (Table 8). Since lateral deviations contained directional information of trajectories, the effect of not only the presence of prism rotation but also the leftness or rightness of prism rotation was reflected in this analysis. The results suggested a significant effect of the prism rotation factor on erroneous movement.

Table 7. The one-way repeated-measures ANOVA for lateral deviations. Maximum indicates maximum lateral deviation. Mean indicates minimum lateral deviation.

	Head R	otation	Prism R	otation	Visual Info.		
	F	р	F	р	F	р	
Maximum	3.483	0.041	20.365	0.000	1.820	0.194	
Mean	3.415	0.044	20.332	0.000	1.915	0.183	

Table 8. The post-hoc test for lateral deviations. *Cor. p* indicates corrected p-value. *Unc. p* indicates uncorrected p-value.

	Head Rotation			Pris	Prism Rotation			Visual Info.		
	Contrast		cor. p	Contrast		cor. p	Contrast		unc. p	
Maximum	0	L30	0.618	None	L30	0.000	On	Off	0.194	
Lateral	0	R30	0.174	None	R30	0.003				
Deviation	L30	R30	0.183	L30	R30	0.001				
Mean	0	L30	0.629	None	L30	0.000	On	Off	0.183	
Lateral	0	R30	0.182	None	R30	0.003				
Deviation	L30	R30	0.189	L30	R30	0.001				

To consider the effect of prism rotation on locomotion, the conditions were divided into conditions with prism rotation and without prism rotation for investigation. There were no significant differences within no prism rotation conditions [max: F(5, 90) = 1.803, p = 0.120; mean: F(5, 90) = 1.712, p = 0.140], but there were significant differences within prism rotation conditions [max: F(3, 54) = 15.676, p = 0.000; mean: F(3, 54) = 15.436, p = 0.000] (Table 9).

In further post-hoc tests on statistically significant results, there were significant differences between the conditions except for between condition 4 and condition 7 [max: t(18) = 0.784, corrected p = 1.000; mean: t(18) = 0.722, corrected p = 1.000] and between conditions 5 and condition 6 [max: t(18) = 1.446, corrected p = 0.165; mean: t(18) = 1.465, corrected p = 0.961] (**Table 10**). Each pair has different head directions but the same prism direction, leading to the assumption that the effect of prism rotation is significant.

Table 9. The one-way repeated-measures ANOVA for lateral deviations in conditions with and without prism rotation. Maximum indicates maximum lateral deviation. Mean indicates minimum lateral deviation.

	With Prisr	n Rotation	Without Prism Rotation		
	F	р	F	р	
Maximum	15.676	0.000	1.803	0.120	
Mean	15.436	0.000	1.712	0.140	

Table 10. The post-hoc test for lateral deviations within prism conditions.

	Cont	trast	t	cor. p
	Condition 4	Condition 5	4.154	0.004
	Condition 4	Condition 6	4.749	0.001
Morrisours	Condition 4	Condition 7	0.784	1.000
Maximum	Condition 5	Condition 6	1.446	0.992
	Condition 5	Condition 7	-3.892	0.006
	Condition 6	Condition 7	-4.131	0.004
	Condition 4	Condition 5	4.115	0.004
	Condition 4	Condition 6	4.713	0.001
Moon	Condition 4	Condition 7	0.722	1.000
Mean	Condition 5	Condition 6	1.465	0.961
	Condition 5	Condition 7	-3.901	0.006
	Condition 6	Condition 7	-4.122	0.004

3.3. The trajectory pattern by phase

As shown in **Figure 4b**, the deviation of the trajectory due to prism rotation did not remain constant for the entire 5 meters. Instead, some sections had particularly large deviations, causing a curved trajectory. Thus, the five phases were compared on lateral deviations by using one-way repeated-measures ANOVAs to investigate the impact of the phase factor. As a result, significant differences were observed [max: F(4, 72) = 7.559, p = 0.000; mean: F(4, 72) = 9.935, p = 0.000].

Post-hoc tests with the Bonferroni correction method were performed to analyze the statistically significant results further. The results showed that lateral deviations of phase 1 were significantly different from those of phase 2, 3, and 4 at p < 0.05 level [phase 1 and 2: t(18) = -3.506, *corrected* p = 0.025; phase 1 and 3: t(18) = -3.690, *corrected* p = 0.017; phase 1 and 4: t(18) = -3.383, *corrected* p = 0.033], and there was an additional difference in mean lateral deviation between phase 2 and phase 3 [phase 1 and 2: t(18) = -4.055, *corrected* p = 0.007; phase 1 and 3: t(18) = -3.985, *corrected* p = 0.009; phase 1 and 4: t(18) = -3.771, *corrected* p = 0.014; phase 2 and 3: t(18) = -3.510, *corrected* p = 0.025] (**Table 11**). As the effects of any factors seemed apparent between phase 1 and phase 2, 3, or 4, the findings suggested that comparing conditions or factors within the same phase

is necessary for further analysis.

	Con	trast	t	cor. p
	Phase 1	Phase 2	-3.506	0.025
	Phase 1	Phase 3	-3.690	0.017
	Phase 1	Phase 4	-3.383	0.033
Movimum	Phase 1	Phase 5	-2.635	0.168
	Phase 2	Phase 3	-3.173	0.053
Maximum	Phase 2	Phase 4	-2.674	0.155
	Phase 2	Phase 5	-1.588	1
	Phase 3	Phase 4	-1.589	1
	Phase 3	Phase 5	-0.139	1
	Phase 4	Phase 5	1.036	1
	Phase 1	Phase 2	-4.055	0.007
	Phase 1	Phase 3	-3.985	0.009
	Phase 1	Phase 4	-3.771	0.014
	Phase 1	Phase 5	-3.149	0.056
ЪЛ	Phase 2	Phase 3	-3.510	0.025
Mean	Phase 2	Phase 4	-2.944	0.087
	Phase 2	Phase 5	-1.832	0.836
	Phase 3	Phase 4	-1.732	1
	Phase 3	Phase 5	-0.277	1
	Phase 4	Phase 5	1.211	1

Table 11. The post-hoc test for lateral deviations between phases.

3.4. The trajectory pattern during sensory mismatch

Since there were similarities between condition 4 and condition 7 and between condition 5 and condition 6, paired-samples t-tests for the two pairs were conducted. To consider the phase factor and analyze the trajectory patterns in more details, the lateral deviations were compared within each phase. The results proved that the trajectory patterns between condition 4 and condition 7 and between condition 5 and condition 6 are statistically similar to each other throughout the entire phases (**Table 12**).

Table 12. The paired-samples t-test for lateral deviations in prism conditions.

		Conditior	n 4 and 7	Condition 5 and 6		
		t	р	t	р	
Phase 1	Max	0.256	0.801	1.823	0.085	
	Mean	-0.129	0.898	1.608	0.125	
Phase 2	Max	0.492	0.629	1.696	0.107	
	Mean	0.475	0.640	1.566	0.135	
Phase 3	Max	0.802	0.433	1.446	0.165	
	Mean	0.786	0.442	1.520	0.146	
Dhago 1	Max	0.890	0.385	1.221	0.238	
rnase 4	Mean	0.897	0.382	1.379	0.185	
Dhaga F	Max	1.154	0.264	1.204	0.244	
Phase 5	Mean	0.902	0.379	1.277	0.218	

As a significant effect of prism rotation was discovered, a further analysis was carried out to compare between no prism rotation conditions and prism rotation conditions using paired-samples t-tests. First, prism conditions and no prism conditions were compared with the same head direction but different visual directions (**Figure 5**). All comparisons showed significant differences between conditions (**Table 13**). However, as the phase went from 2 to 5, the p-values increased. Even in phase 5 of the comparison between condition 5 and condition 1, the p-value was greater than 0.05, suggesting the similarity between each pair of conditions in phase 5.

Next, prism conditions and no prism conditions were compared, with different head directions but the same visual direction (**Figure 6**). There were significant differences between conditions from all comparisons (**Table 14**). Although the p-values in phase 5 were not greater than 0.05, yet still increased compared to phase 2, 3, and 4.

These results indicate that both head direction and prism direction influence the locomotion pattern in such incompatible situations. The findings suggest that the trajectory was controlled and corrected from the significant effect of prism rotation as the participants became closer to the target.





Figure 5. Lateral deviation of conditions with the same head direction and different visual directions. (a), (b): comparison between condition 6 and 2. (c), (d): between condition 7 and 3. (e), (f): comparison between condition 4 and 1. (g), (h): comparison between condition 5 and 1. The red dashed line represents x = 0. Gray box indicates 0° prism rotation, green box indicates right 30° prism rotation, purple box indicates left 30° prism rotation. The left column's figures represent maximum lateral deviations. The right column's figures represent mean lateral deviations.

Condition		6 and 2		7 and 3		4 and 1		5 and 1	
		t	р	t	р	t	р	t	р
Dhaga 1	Max	-3.027	0.007	4.160	0.001	4.819	0.000	-2.310	0.033
Phase 1	Mean	-2.776	0.012	3.867	0.001	4.423	0.000	-2.396	0.028
Phase 2	Max	-3.416	0.003	4.411	0.000	4.869	0.000	-2.507	0.022
	Mean	-3.375	0.003	4.268	0.000	4.691	0.000	-2.685	0.015
Phase 3	Max	-3.106	0.006	3.528	0.002	5.015	0.000	-2.236	0.038
	Mean	-3.194	0.005	3.601	0.002	4.827	0.000	-2.338	0.031
Dhaga (Max	-2.732	0.014	2.971	0.008	5.036	0.000	-2.115	0.049
Phase 4	Mean	-2.880	0.010	2.920	0.009	4.911	0.000	-2.130	0.047
Dhasa F	Max	-2.352	0.030	2.113	0.049	4.959	0.000	-1.689	0.108
Phase 5	Mean	-2.434	0.026	2.216	0.040	4.702	0.000	-1.748	0.097

Table 13. The paired-samples t-test for lateral deviations in the same head direction and different visual directions.





Figure 6. Lateral deviation of conditions with different head directions and the same visual direction. (a), (b): comparison between condition 4 and 2. (c), (d): comparison between condition 5 and 3. (e), (f): between condition 6 and 1. (g), (h): comparison between condition 7 and 1. The red dashed line represents x = 0. Gray box indicates 0° prism rotation, green box indicates right 30° prism rotation, purple box indicates left 30° prism rotation. The left column's figures represent maximum lateral deviations. The right column's figures represent mean lateral deviations.

Table	14.	The	paired-s	amples	t-test	for	lateral	deviations	in
differe	ent he	ead di	rections	and the	same vi	sual	directio	n.	

Condition		4 and 2		5 and 3		6 and 1		7 and 1	
		t	р	t	р	t	р	t	р
Dhaga 1	Max	5.228	0.000	-4.216	0.001	-3.526	0.002	5.840	0.000
rnase i	Mean	4.908	0.000	-3.959	0.001	-3.497	0.003	5.669	0.000
Phase 2	Max	5.038	0.000	-3.575	0.002	-3.417	0.003	5.062	0.000
	Mean	4.867	0.000	-3.682	0.002	-3.416	0.003	4.939	0.000
Dhana 2	Max	5.020	0.000	-3.322	0.004	-2.963	0.008	4.290	0.000
Phase 5	Mean	4.948	0.000	-3.320	0.004	-3.120	0.006	4.241	0.000
Dhago 1	Max	5.069	0.000	-3.256	0.004	-2.772	0.013	3.864	0.001
Phase 4	Mean	5.000	0.000	-3.214	0.005	-2.889	0.010	3.275	0.002
Phase 5	Max	4.641	0.000	-2.676	0.015	-2.549	0.020	3.069	0.007
	Mean	4.575	0.000	-2.748	0.013	-2.636	0.017	3.156	0.005

Chapter 4. Discussion

The present study employed a target-oriented locomotion task in which participants walked directly toward a target for a distance of 5 meters in a virtual reality environment. The investigation focused on analyzing locomotion trajectories under conditions of consistent and inconsistent vestibular and visual cues, aiming to understand the cues utilized by individuals during navigation. The findings pertaining to the consistent conditions revealed that participants predominantly relied on both visual and vestibular cues to guide their locomotion. In contrast, the inconsistent conditions involved the manipulation of visual information through prism rotation, highlighting the examination of the updating process of internal representations of movement during sensory information conflict.

Previous studies (Crowell et al., 1998; Warren, 1998) have underscored that visual and vestibular cues need to communicate for accurate perception of self-motion. Even in situations where it is difficult to rely on visual cues (e.g., at night, during fog), it is possible to walk generally based on an internal representation built over time through the integration of sensory information about self-motion (Loomis et al., 2001; Ivaneko et al., 2011). In the present study, trajectory deviations resulting from head direction were not significant when vestibular and visual cues were consistent (conditions 1, 2, 3), and the absence of visual information by closing the eyes did not lead to substantial trajectory deviations either (conditions 8, 9, 10). These findings suggest that under normal circumstances in which the vestibular and visual cues align, the sensory cues communicate with each other, facilitating a relatively straight-line walk toward the target. Furthermore, even without visual information, the previously built internal representation is still utilized to enable usual locomotion.

However, the question arises as to whether visual and vestibular cues continue communicating similarly when they provide inconsistent information. According to Cardinali et al. (2009), the internal representation cannot accept inconsistency when visual and vestibular cues provide different information about a movement. The results of the present study align with this notion, indicating a significant impact of sensory information conflict on locomotion. Specifically, the presence of prism rotation significantly influenced overall movement parameters, including increased travel distance and time, decreased average speed and movement error, such as lateral deviations. Moreover, the effect of head rotation and visual information did not yield significant findings in the analysis.

Cardinali et al. (2009) further suggested that the brain follows the direction indicated by a single sensory cue when there is an

inconsistency between two sensory cues. Similarly, the brain has to investigate if the sensory cues have the same source (Berger & Bulthoff, 2009). Notably, integration of the sensory signals occurs if they have the same source (Pouget et al., 2004; Ernest, 2007; Berger & Bulthoff, 2009) while selective attention on one cue and ignorance on the other happen if they do not (Berger & Bulthoff, 2009). Hence, this study aimed to investigate the update process of the internal representation by examining which cue, whether visual or vestibular, plays a more prominent role during sensory mismatch.

Previous studies that used manipulated optic flow (Warren et al., 2001; Warren & Hannon, 1988) have demonstrated the influence of visual cues of self-motion on the direction of movement. If visual cues for self-motion were more dominant over vestibular cues, trajectories would exhibit a bias toward the direction indicated by the visual cues, regardless of head direction (Warren et al., 2001; Warren & Hannon, 1988). As investigation of this dominance, comparisons between the conditions with the same head direction but different visual scenes due to the absence or presence of prism rotation were carried out in the present study. The results showed a significant effect of visual cues, aligning with previous findings and suggesting that updating the internal representation relies on visual cues.

However, previous studies have suggested that vestibular cues influence the direction of movement (Kennedy et al., 2003; Harris et al., 2000; Telford et al., 1995). Consequently, comparisons between the conditions with the same visual scenes but different head directions were made. If vestibular cues for self-motion were more dominant over visual cues, trajectories should exhibit a bias toward the head direction (Carlsen et al., 2005). The results of the present study also showed a significant difference, suggesting that updating the internal representation is influenced by the head direction and continues to rely on vestibular cues. These findings suggest that in situations where visual and vestibular cues are incompatible, giving rise to sensory mismatch, the effects of both cues on the internal representation updating process are significant.

Still, the locomotion trajectories deviated from x = 0 in the sensory mismatch conditions (conditions 4, 5, 6, 7). If both cues had effectively communicated, the locomotion trajectories would have resembled a straight line, as shown in conditions 1, 2, 3. However, the observed significant deviations suggest the involvement of an additional type of information in spatial navigation: external cues. Consequently, the effect of external cues, providing static information about the external environment, was examined by focusing specifically on the perceived location.

In conditions 4 and 5, while the head was facing forward toward the target, the prism rotation was applied as 30° to the left and 30° to the right. As a result, the target was located on the right visual field in condition 4, as if the head were turned leftward from the target (similar to condition 2). In contrast, the target was located on the left visual field in condition 5, as if the head were turned rightward from the target (similar to condition 3). Consequently, participants exhibited a rightward-biased trajectory toward the target in condition 4, where the target was perceived in the right visual field. Similarly, in condition 5, participants displayed a leftward-biased trajectory toward the target, which was perceived in the left visual field.

This effect was also observed in conditions 6 and 7. In both conditions, the head was rotated to the left and right, respectively, but the prism rotation was applied in the opposite direction. Consequently, the prism rotation eventually balanced out the effect of the head rotation as if the head had not been rotated, thereby maintaining the target at the center of the visual field. Thus, participants continued to move in the direction their head was facing, perceiving the target as if it were in front of them. As revealed by the results, the trajectories in condition 6 exhibited a leftward deviation, and the trajectories in condition 7 showed a rightward deviation.

These findings can be linked to studies investigating locomotion based on the perceived target direction. Previous studies have explored whether individuals move toward the visually perceived target or in the direction of optic flow (Rushton et al., 1998; Warren et al., 2001). As mentioned in the introduction section, the optic flow theory states that humans move in the optic flow direction to compensate for the discrepancy between the perceived direction and the target, aligning the focus of expansion with the target (Warren et al., 2001). Warren et al. (2001) found that trajectories were influenced by optic flow, suggesting its significant impact on direction perception during locomotion.

In contrast, Rushton et al. (1998) reported movement trajectory deviations when participants could not accurately discern the target's correct location due to prism glasses, indicating that individuals move in the direction of the perceived target. However, Warren et al. (2001) demonstrated that increasing the intensity of optic flow by adding more visual structures to the floor resulted in smaller errors in trajectory, further supporting the optic flow theory. As shown in the results of the current study, optic flow still plays a vital role in spatial perception. However, this study did not involve such intense optic flow, suggesting that individuals predominantly follow the perceived target direction unless the optic flow is significantly altered with high intensity.

Overall, findings underscore importance these the of understanding how sensory cues are employed in the updating of internal representations for spatial perception rather than simply emphasizing the dominance of either visual or vestibular information. Furthermore, to successfully navigate toward a goal, individuals rely on internal representations built on sensory information and newly acquired information about self-motion and the external world under normal circumstances but follow the perceived location of the target during incompatibility between sensory information. Building upon these insights, further research should explore approaches to enhance the spatial perception of individuals facing challenges in integrating sensory information and to mitigate cybersickness issues arising from sensory information conflict in virtual reality settings.

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가상현실에서 지각된 목표를 향한 보행: 시각과 전정 정보 간 상충의 영향

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목표를 향해 성공적으로 이동하기 위해 인간은 움직임에 대한 감각 정보를 기반으로 내부 표상을 구축하고 이를 지속적으로 갱신한다. 인간은 내부 단서에 의존하여 내부 표상을 수정하는데, 이는 일반적으로 망막에 맺히는 움직임 패턴인 광학 흐름과 전정 기관을 통해 감지된 회전 및 선형 가속도 정보를 기반으로 이루어진다. 이러한 내부 단서 외에도 인간은 외부 단서를 활용하여 외부 환경에 대해 이해하며, 이를 통해 공간 상에서 정확하게 이동할 수 있다.

본 연구에서는 내부 단서가 내부 표상을 갱신하는 데 어떻게 활용되는지, 더 나아가 내부 단서가 서로 상충될 때 외부 단서가 어떻게 활용되는지를 조사하였다. 이를 위해, 본 연구에서 참여자들은 가상현실 환경에서 5 미터의 목표 지향적 보행 과제에 참여하였다. 총 10개의 실험 조건은 머리 방향(0°, 좌 30°, 우 30°), 프리즘 회전(0°, 좌 30°, 우 30°), 시각 정보의 유무를 토대로 만들어졌다. 해당 요인들이 전반적인 움직임과 보행 궤적에 미치는 영향을 분석하였고, 시각 단서와 전정 단서가 일치하거나 일치하지 않을 때의 보행 궤적을 비교하였다.

본 연구 결과, 프리즘 회전이 보행 거리, 시간, 속도 및 궤적의 치우침에 유의미한 영향을 미치는 것으로 나타났으며, 전정 단서와 시각 단서가 서로 상충된 경우에는 둘 중 어느 단서도 특별히 우세하지 않은 것으로 나타났다. 그 대신, 목표물의 지각된 위치인 외부 시각 단서의 영향이 존재함을 확인하였다.

본 연구 결과를 통해 공간 지각에서의 감각 정보 활용 양상을 설명하였다. 더불어, 본 연구는 감각 정보 통합에 어려움을 겪는 환자들의 공간 지각 재활을 위한 후속 연구와 감각 정보 간의 불일치로 인해 발생하는 가상현실의 사이버멀미 저감을 위한 후속 연구로 이어질 것으로 예상된다.

주요어: 목표 지향적 보행, 가상현실, 프리즘 회전, 광학 흐름, 전정 정 보, 지각된 목표

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