Linear Path Integration Deficits in Patients with Abnormal Vestibular Afference

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Abstract
Effective navigation requires the ability to keep track of one’s location and maintain orientation during linear and angular displacements. Path integration is the process of updating the representation of body position by integrating internally-generated self-motion signals over time (e.g., walking in the dark). One major source of input to path integration is vestibular afference. We tested patients with reduced vestibular function (unilateral vestibular hypofunction, UVH), patients with aberrant vestibular function (benign paroxysmal positional vertigo, BPPV), and healthy participants (controls) on two linear path integration tasks: experimenter-guided walking and target-directed walking. The experimenter-guided walking task revealed a systematic underestimation of self-motion signals in UVH patients compared to the other groups. However, we did not find any difference in the distance walked between the UVH group and the control group for the target-directed walking task. Results from neuropsychological testing and clinical balance measures suggest that the errors in experimenter-guided walking were not attributable to cognitive and/or balance impairments. We conclude that impairment in linear path integration in UVH patients stem from deficits in self-motion perception. Importantly, our results also suggest that patients with a UVH deficit do not lose their ability to walk accurately without vision to a memorized target location.

Keywords
Vestibular navigation, vestibular hypofunction, path integration, spatial orientation

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1. Introduction

Human spatial orientation and navigation rely on the crucial ability to sense self-motion during linear and angular displacements. The ability to keep track of our location and maintain orientation is so essential to our daily lives that those without this skill are significantly disabled. Vision provides multiple sources of information for determining self-position and orientation in external space. However, in the absence of vision, we retain the ability to remain oriented by relying upon internally-generated (idiopathic) self-motion signals such as proprioceptive cues from the musculature and acceleration signals from the vestibular end organs (Highstein, 1996; Israël and Berthoz, 1989). These signals are then referenced to a remembered spatial origin or target location in working memory, along with a method of updating one’s current position and orientation in space, known as path integration or dead reckoning (Etienne et al., 1996; Loomis et al., 1999; Mittelstaedt and Mittelstaedt, 1980).

There is extensive evidence from animal studies suggesting that the vestibular system is vital in path integration and spatial navigation (Barlow, 1964; Beritoff, 1965; Cullen and Roy, 2004; Etienne et al., 1996; Mittelstaedt and Mittelstaedt, 1980, Wallace et al., 2002). Rats with unilateral and bilateral vestibular lesions display deficits in spatial memory and navigation tasks, such as the water maze, radial arm maze, T-maze and foraging tasks (Russell et al., 2003; Stackman and Herbert, 2002; Wallace et al., 2002; Zheng et al., 2006, 2009). In these studies, the rats were tested months after labyrinthectomy, suggesting that any impairment in path integration was not related to acute vestibular or locomotor deficits. Interestingly, the spatial memory and navigational deficits were manifest differently depending on the type of lesion and type of task. Rats with unilateral vestibular deafferentation (UVD) initially showed impairments on a spatial navigation task (food foraging in the dark), which resolved six months after the onset of the lesion (Zheng et al., 2006). In contrast, although rats with bilateral vestibular deafferentation (BVD) were able to complete the same task in the light, they had chronic deficits when tested in darkness (Zheng et al., 2009). These data suggest that vestibular afference is essential for spatial orientation and navigation, likely by informing the brain about changes in head and body orientation in space during self-motion.

In humans, there is limited but emerging evidence for the role of vestibular afference in path integration. Behavioral testing using a ‘blind walking’ paradigm has been the main method for assessing path integration in humans. In a typical blind walking task, blindfolded participants attempt to walk without vision to a previously viewed target location. Using this approach it has been shown that healthy humans can estimate changes in body location and orientation at distances up to 20 m or more and precisely walk to the target location without vision (Loomis et al., 1992; Philbeck and Loomis, 1997; Thomson, 1983; for a review see Mittelstaedt and Mittelstaedt, 2001). In contrast, patients with vestibular deficits show veering and other impairments, during similar non-visually guided walking tasks (Borel et al., 2004; Cohen, 2000; Cohen and Kimball, 2002; Guidetti et al., 2008; Péruch et al., 1999,