Dyscalculia and vestibular function

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Abstract

Background: A few studies in humans suggest that changes in stimulation of the balance organs of the inner ear (the ‘vestibular system’) can disrupt numerical cognition, resulting in ‘dyscalculia’, the inability to manipulate numbers. Many studies have also demonstrated that patients with vestibular dysfunction exhibit deficits in spatial memory.

Objectives: It is suggested that there may be a connection between spatial memory deficits resulting from vestibular dysfunction and the occurrence of dyscalculia, given the evidence that numerosity is coupled to the processing of spatial information (e.g., the ‘spatial numerical association of response codes (‘SNARC’) effect’).

Results and Conclusion: The evidence supporting this hypothesis is summarised and potential experiments to test it are proposed.

Introduction

It was first reported in the early 1990s that people with damage to the balance organs of the inner ear (the ‘vestibular system’), exhibited deficits in memories for places in the environment (i.e., ‘spatial memory’) [see [1] for review]. Given that the vestibular system detects movement of the head in three dimensional space, performs complex mathematical computations of acceleration, velocity and position of the head [2] and communicates this information to higher centres of the brain [3–6], this was perhaps not entirely surprising. The first clinical evidence was published by Grimm et al. in 1989 [7], who reported that patients with a perilymph fistular syndrome (a rupture in the vestibular labyrinth, resulting in leakage of perilymphatic fluid) experienced not only vestibular symptoms (e.g., positional vertigo) but also a variety of cognitive and emotional symptoms, including memory and attention deficits, anxiety and depression. From a total sample of 102 patients, more than 85% reported memory loss of some sort. Despite a normal level of intellectual function, performance on digit symbol, block design, paired associate learning and picture arrangement tasks, was impaired.

Since this study, many papers have been published documenting specific spatial memory and attention deficits in patients with different kinds of vestibular disorders ([8–24]; see [25–27] for reviews). Given the severity of the symptoms in some vestibular disorders such as Meniere’s disease, it is possible that cognitive dysfunction is an indirect consequence of symptoms such as vertigo. However, studies of patients with chronic vestibular loss, and without vertigo, have still demonstrated spatial memory impairment [15], even 5–10 years after complete bilateral vestibular loss [12].

Numerous studies in animals have also demonstrated that unilateral or bilateral lesions of the vestibular system disrupt spatial memory [28–45]. The effects of bilateral vestibular loss (bilateral vestibular deafferentation, BVD) are particularly profound and have been shown to last for at least 14 months [28]. These spatial memory deficits are not simply the result of an inability to move, since these animals are hyperactive. However, regression analyses show that the extent of the spatial memory deficits cannot be predicted from the degree of hyperactivity [28]. Neurophysiological studies have shown that BVD causes an impairment of the function of place cells [46,47] and theta rhythm [44,48,49] in the hippocampus, which are related to spatial memory. Humans with bilateral vestibular loss have even been demonstrated to exhibit a bilateral atrophy of the hippocampus of approximately 17% [12].

The link between vestibular dysfunction and anxiety/depression is well recognised clinically and is believed to be due to more than living with the burden of a vestibular disorder [50–57]. Not only do patients with vestibular disorders frequently experience symptoms of anxiety and depression, but those with anxiety and depression can experience vestibular disorders [58–60]. There appears to be a complex, two-way interaction between vestibular function and affective state, which may be partly related to the contribution of the vestibular system to the control of autonomic function (e.g., heart rate, blood pressure, respiration) [50–57]. This kind of evidence suggests that vestibular impairment may cause a multitude of changes in cognition, emotion and personality, which

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is consistent with some evidence that vestibular disease is associated with unusually high rates of depersonalization/derealization symptoms, which include difficulty focussing attention and thoughts seeming blurred (e.g., [16,17]).

Whether the cognitive deficits associated with vestibular damage are limited to spatial memory impairment is unclear. Some human studies have reported that other aspects of memory and general intelligence are normal [12]. Some animal studies using BVD have reported deficits in object recognition memory [61] and more recently, using the 5 choice serial reaction time task (5-CSRTT), substantial attentional deficits [62,63]. In these latter studies, the percentage of correct responses was significantly less in the BVD group compared to sham controls, and the percentage of incorrect responses greater; however, there was no significant difference between the two groups in the number of omissions, indicating once again that the performance deficits for the BVD rats were not due to an inability to respond.

**Dyscalculia and vestibular function**

Amongst these reports of cognitive deficits that are ostensibly independent of spatial memory, a few researchers have reported a link between vestibular function and dyscalculia, the inability to manipulate numbers [19,24]. Yardley et al. [24] investigated the effects of having to continuously monitor body position during vestibular stimulation, on the ability to perform mental arithmetic. Arithmetic performance was significantly degraded in this dual task situation. Risey and Briner [19] examined patients with vertigo of central origin and observed that when they were asked to count backwards by two, they displaced decades. This error did not occur when the same subjects were provided with visual information. Although these appear to be the only two studies relating to this subject that are published in peer-reviewed journals, anecdotal evidence would suggest that the phenomenon is reasonably common amongst patients with vestibular disorders. Certainly no conclusions could be reached based on only two studies, which are open to other interpretations, such as the possibility that performance in any cognitive task would be degraded in the presence of a change in vestibular stimulation. However, the possibility of a connection to other cognitive deficits associated with vestibular dysfunction, is intriguing.

‘Numerosity’ or the ‘concept of number’, has been attributed not only to primates [64] but also to lower mammalian species such as the rat [65,66], and more recently, to pigeons [67]. Numerosity is the cognitive skill with which numbers are manipulated abstractly in order to apply them to new information. For example, understanding the relationship between 10 and 1 means that the numbers 8 and 4 can be interpreted in relation to one another as well as to other numbers. However, evidence suggests that numerosity is tightly coupled to the processing of spatial information. For example, when subjects are asked to respond to numbers by pressing a left or a right response key, they tend to respond to small numbers faster with the left hand than the right hand, and large numbers faster with the right hand than the left hand (the so-called ‘spatial numerical association of response codes (‘SNARC’ effect’) [68–73].

The possible connection between dyscalculia and vestibular dysfunction has gone unexplained for over 20 years. However, the link between numerosity and spatial memory, which is supported by, amongst other evidence, the SNARC effect, suggests the intriguing possibility that disruption of vestibular function affects the ability to process both numerical and spatial information, and that the disruption of spatial memory by vestibular dysfunction leads to the disruption of numerical cognition. Consistent with this hypothesis, a recent study has shown that natural vestibular stimulation in humans can substantially affect the processing of numbers [74]. Animal studies have shown that complete inactivation of the vestibular system results in deficits in the ability of rats to accurately time their responses in a five choice serial reaction time task [61,62].

Two brain regions that are known to be important in numerical cognition in primates are the ventral intraparietal cortex (VIP) and the prefrontal cortex (PFC) (the rat homologues are the posterior parietal cortex (PPC) and the lateral prefrontal cortex [64,68]). Coincidentally, the VIP is known to be a major vestibular projection area in the primate neocortex [3–6] and neurochemical changes have been demonstrated in the rat PFC following vestibular lesions [75,76].

**Hypothesis**

Activation of the vestibular system contributes to numerical discrimination and memory, and the response of neurons in the brain that encode number, by providing head movement and position information that is necessary for normal spatial memory. Consequently, artificial activation or inactivation of the vestibular system will disrupt the normal influence of this sensory system on numerosity. Dyscalculia in patients with vestibular dysfunction is likely to be a result of impaired spatial memory caused by the loss of normal vestibular function. One way of testing this hypothesis would be to activate (using galvanic vestibular stimulation, i.e. bipolar electrical stimulation of the inner ear with the cathode on one side or the other) or inactivate (using unilateral surgical lesions) the vestibular system and examine the effects on the performance of rats in a conditioned behavioural task requiring the abstract manipulation of numbers, specifically a task requiring the numerical discrimination and memory of auditory tones [66]. Because activation or inactivation would be unilateral only, auditory function would be intact in the remaining ear. The abstract numerical competence of rats would have to be quantified in a way that is not confounded by non-numerical cues and whether they abide by Weber’s law (i.e., the discriminability of two numbers is a function of their ratio) would have to be investigated [66], and compared to control groups (unilateral sham electrical stimulation and unilateral sham surgery, respectively). Furthermore, the responses of neurons in the lateral PFC and the PPC (the rat homologue of the primate VIP), could be chronically recorded and compared to response patterns (spike frequency in relation to behavioural performance) in the control groups. The behavioural experiments could also be carried out in vestibular-intact humans receiving galvanic vestibular stimulation or patients with unilateral vestibular disorders; the neurophysiological experiments could best be conducted in non-human primates in which recordings could be made from the VIP itself [3].

The concept of number is one of the defining characteristics of higher consciousness. Understanding the link between the vestibular system, which detects head movement through space (and time), and the representation of the concept of number in the brain, will lead to a better understanding of how the vestibular inner ear contributes to cognition and the neural processes that subserve it, as well as a better understanding of the cognitive disabilities of people with vestibular dysfunction.

**One sentence summary:** Dyscalculia in patients with vestibular disorders may be related to the spatial memory deficits that have been demonstrated.

**Conflict of Interest**

None declared.
References


