Medical Hypotheses 79 (2012) 493–496

Contents lists available at SciVerse ScienceDirect

Medical Hypotheses

journal homepage: www.elsevier.com/locate/mehy

Dyscalculia and vestibular function

P.F. Smith *

Dept. Pharmacology, University of Otago, Dunedin, New Zealand

ARTICLE INFO

Article history:
Received 2 May 2012
Accepted 26 June 2012

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

* Fax: +64 3 479 9140.
E-mail address: paul.smith@otago.ac.nz

0306-9877/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mehy.2012.06.032

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

[1] Smith PF, Darlington CL, Zheng Y. Move it or lose it: is stimulation of the vestibular system necessary for normal spatial memory? Hippocampus 2010;20:36–43.
[2] Hanes DA. Mathematical requirements of visual-vestibular integration. J Math Biol 2012, in press.
[3] Cullen KE. The vestibular system: multimodal integration and encoding of self-motion for motor control. Trends Neurosci 2012;35:185–96.
[4] Dieterich M, Brandt T. Functional brain imaging of peripheral and central vestibular disorders. Brain 2008;131(Pt 10):2538–52.
[5] Ventre-Dominey J, Nighoghossian N, Denise P. Interaction between cortical control of vestibular function and spatial representation in man. Ann NY Acad Sci 2005;1039:494–7.
[6] Ventre-Dominey J, Vallee B. Vestibular integration in human cerebral cortex contributes to spatial remapping. Neuropsychologia 2007;45(2):435–9.
[7] Grimm RJ, Hemenway WG, Lebray PR, Black FO. The perilymph fistula syndrome defined in mild head trauma. Acta Otolaryngol (Stockh) 1989; (Suppl. 464): 1-40.
[8] Andersson G, Hagman J, Talianzadeh R, Svedberg A, Larsen HC. Effects of cognitive load on postural control. Brain Res Bull 2002;58:135–9.
[9] Andersson G, Hagman J, Talianzadeh R, Svedberg A, Larsen HC. Dual task study of cognitive and postural interference in patients with vestibular disorders. Otol Neurotol 2003;24:289–93.
[10] Borel L, Harlay F, Lopez C, Magnan J, Chays A, Lacour M. Walking performance in vestibular-defective patients before and after unilateral vestibular neurrectomy. Behav Brain Res 2004;150:191–200.
[11] Black FO, Pesznecker S, Stallings V. Permanent gentamicin vestibulotoxicity. Otol Neurotol 2004;25(4):559–69.
[12] Brandt T, Schautzer F, Hamilton DA, Bruning R, Markowitsch H, Kalla R, et al. Vestibular loss causes hippocampal atrophy and impaired spatial memory in humans. Brain 2005;128:2732–41.
[13] Cohen HS. Vestibular disorders and impaired path integration along a linear trajectory. J Vestib Res 2000;10:7–15.
[14] Cohen HS, Kimball KT. Improvements in path integration after vestibular rehabilitation. J Vestib Res 2002;12:47–51.
[15] Guidetti G, Monzani D, Trebbi M, Rovatti V. Impaired navigation skills with psychological distress and chronic peripheral vestibular hypofunction without vertigo. Arch Otorhinolarngol Ital 2008;28:21–5.
[16] Jauregui-Renaud K, Ramos-Toledo V, Aguilar-Bolanos M, Montano-Velazquez B, Pliego-Maldonado A. Symptoms of detachment from the self or from the environment in patients with an acquired deficiency of the special senses. J Vest Res 2008;18:129–37.
[17] Jauregui-Renaud K, Sang FY, Gresty MA, Green DA, Bronstein AM. Depersonalisation/derealisation symptoms and updating orientation in patients with vestibular disease. J Neurol Neurosurg Psychiat 2008;79:276–83.
[18] Peruch P, Borel L, Gaunet F, Thinus-Blanc G, Magnan J, Lacour M. Spatial performance of unilateral vestibular defective patients in nonvisual versus visual navigation. J Vest Res 1999;9:37–47.
[19] Risey J, Briner W. Dyscalculia in patients with vertigo. J Vestib Res 1990–1991;1:31–7.
[20] Redfern MS, Talkowski ME, Jennings JR, Furman JM. Cognitive influences in postural control of patients with unilateral vestibular loss. Gait Posture 2004;19:105–14.
[21] Schautzer F, Hamilton D, Kalla R, Strupp M, Brandt T. Spatial memory deficits in patients with chronic bilateral vestibular failure. Ann NY Acad Sci 2003;1004:316–24.
[22] Talkowski ME, Redfern MS, Jennings JR, Furman JM. Cognitive requirements for vestibular and ocular motor processing in healthy adults and patients with unilateral vestibular lesions. J Cog Neurosci 2005;17:1432–41.
[23] Yardley L, Gardner M, Bronstein A, Davies R, Buckwell D, Luxon L. Interference between postural control and mental task performance in patients with vestibular disorders and healthy controls. J Neurol Neurosurg Psychiat 2001;71:48–542.
[24] Yardley L, Papo D, Bronstein A, Gresty M, Gardner M, Lavie N, et al. Attentional demands of continuously monitoring orientation using vestibular information. Neuropsychologia 2002;40:373–83.
[25] Smith PF, Zheng Y, Horii A, Darlington CL. Does vestibular damage cause cognitive dysfunction in humans? J Vest Res 2005;15:1–9.
[26] Smith PF, Brandt T, Strupp M, Darlington CL, Zheng Y. Balance before reason in rats and humans. Ann NY Acad Sci 2009;1164:127–33.
[27] Hanes DA, McCollum G. Cognitive-vestibular interactions: a review of patient difficulties and possible mechanisms. J Vest Res 2006;16(3):75–91.
[28] Baek J-H, Zheng Y, Darlington CL, Smith PF. Evidence that spatial memory deficits in rats following bilateral vestibular loss may be permanent. Neurobiol Learn Mem 2010;94:402–13.
[29] Chapuis N, Krimm M, de Waele C, Vibert N, Berthoz A. Effect of post-training unilateral labyrinthectomy in a spatial orientation task by guinea pigs. Behav Brain Res 1992;51:115–26.
[30] Horn KM, DeWitt JR, Nielson HC. Behavioral assessment of sodium arsanilate induced vestibular dysfunction in rats. Physiol Psychol 1981;9:371–8.
[31] Miller SM, Potegal L, Abraham L. Vestibular involvement in a passive transport and return task. Physiol Psychol 1983;11:1–10.
[32] Mathews BL, Campbell KA, Deadwyler SA. Rotational stimulation disrupts spatial learning in fornix-lesioned rats. Behav Neurosci 1988;102:35–42.
[33] Mathews BL, Ryu JH, Bockaneck C. Vestibular contribution to spatial orientation. Evidence of vestibular navigation in an animal model. Acta Otolaryngol (Stockh.) 1989;468:149–54.
[34] Ossenkopp KP, Hargreaves EL. Spatial learning in an enclosed eight-arm maze in rats with sodium arsinilate-induced labyrinthectomies. Behav Neural Biol 1993;59:253–7.
[35] Potegal M, Day MJ, Abraham L. Maze orientation, visual and vestibular cues in two-maze spontaneous alternation of rats. Physiol Psychol 1977;5:414–20.
[36] Russell N, Horii A, Smith PF, Darlington CL, Bilkey D. Effects of bilateral vestibular deafferentation on radial arm maze performance. J Vest Res 2003;13:9.
[37] Schaeppi U, Krinke G, FitzGerald RE, Classen W. Impaired tunnel-maze behavior in rats with sensory lesions: vestibular and auditory systems. Neurotoxicology 1991;12(3):445–54.
[38] Semenov LV, Bures J. Vestibular stimulation disrupts acquisition of place navigation in the Morris water tank task. Behav Neural Biol 1989;51:346–63.
[39] Stackman RW, Herbert AM. Rats with lesions of the vestibular system require a visual landmark for spatial navigation. Behav Brain Res 2002;128:27–40.
[40] Wallace DG, Hines DJ, Pellis SM, Whishaw IQ. Vestibular information is required for dead reckoning in the rat. J Neurosci 2002;15:10009–17.
[41] Zheng Y, Darlington CL, Smith PF. Impairment and recovery on a food foraging task following unilateral vestibular deafferentation in rat. Hippocampus 2006;16:368–78.
[42] Zheng Y, Goddard M, Darlington CL, Smith PF. Bilateral vestibular deafferentation impairs performance in a spatial forced alternation task in rats. Hippocampus 2007;17:253–6.
[43] Zheng Y, Goddard M, Darlington CL, Smith PF. Long-term deficits on a foraging task after bilateral vestibular deafferentation in rats. Hippocampus 2009;19:480–6.
[44] Neo P, Carter D, Zheng Y, Smith PF, Darlington CL, McNaughton N. Septal elicitation of hippocampal theta rhythm did not repair the cognitive and emotional deficits resulting from vestibular lesions. Hippocampus 2012;22:1176–87.
[45] Besnard S, Machado ML, Vignaux G, Boulouard M, Coquerel A, Bouet V, et al. Influence of vestibular input on spatial and nonspatial memory and on hippocampal NMDA receptors. Hippocampus 2012;22(4):814–26.
[46] Russell N, Horii A, Smith PF, Darlington CL, Bilkey D. The long-term effects of permanent vestibular lesions on hippocampal spatial firing. J Neurosci 2003;23:6490–8.
[47] Stackman RW, Clark AS, Taube JS. Hippocampal spatial representations require vestibular input. Hippocampus 2002;12:291–303.
[48] Russell N, Horii A, Smith PF, Darlington CL, Bilkey D. Lesions of the vestibular system disrupt hippocampal theta rhythm in the rat. J Neurophysiol 2006;96:4–14.
[49] Tai SK, Ma J, Ossenkopp KP, Leung LS. Activation of immobility-related hippocampal theta by cholinergic septohippocampal neurons during vestibular stimulation. Hippocampus 2012;22(4):914–25.
[50] Balaban CD. Neural substrates linking balance control and anxiety. Physiol Behav 2002;77(4–5):469–75.
[51] Balaban CD. Projections from the parabrachial nucleus to the vestibular nuclei: potential substrates for autonomic and limbic influences on vestibular responses. Brain Res 2004;996(1):126–37.
[52] Balaban CD, Thayer JF. Neurological bases for balance-anxiety links. J Anxiety Disord 2001;15(1–2):53–79.
[53] Furman JM, Jacob RG. A clinical taxonomy of dizziness and anxiety in the otoneurological setting. J Anxiety Disord 2001;15(1–2):9–26.
[54] Staab JP. Chronic dizziness: the interface between psychiatry and neurootology. Curr Opin Neurol 2006;19(1):41–8.
[55] Yavorcik KJ, Reighard DA, Misra SP, Cotter LA, Cass SP, Wilson TD, et al. Effects of postural changes and removal of vestibular inputs on blood flow to and from the hindlimb of conscious felines. Am J Physiol Regul Integr Comp Physiol 2009;297(6):R1777–84.
[56] Yates BJ, Billig I, Cotter LA, Mori RL, Card JP. Role of the vestibular system in regulating respiratory muscle activity during movement. Clin Exp Pharmacol Physiol 2002;29(1–2):112–7.
[57] Wilkinson KA, Maurer AP, Sadacca BF, Yates BJ. Responses of feline medial medullary reticular formation neurons with projections to the C5–C6 ventral horn to vestibular stimulation. Brain Res 2004;1018(2):247–56.
[58] Staab JP, Ruckenstein MJ. Which comes first? Psychogenic dizziness versus otogenic anxiety. Laryngoscope 2003;113(10):1714–8.
[59] Furman JM, Redfern MS, Jacob RG. Vestibulo-ocular function in anxiety disorders. J Vest Res 2006;16(4–5):209–15.
[60] Venault P, Rudrauf D, Lepicard EM, Berthoz A, Jouvent R, Chapouthier G. Balance control and posture in anxious mice improved by SSRI treatment. NeuroReport 2001;12(14):3091–4.
[61] Zheng Y, Darlington CL, Smith PF. Bilateral vestibular deafferentation impairs object recognition in rat. NeuroReport 2004;15:1913–6.
[62] Zheng Y, Balabhadrapatruni S, Munn O, Masumura C, Darlington CL, Smith PF. Evidence for deficits in a 5 choice serial reaction time task in rats with bilateral vestibular deafferentation. Behav Brain Res 2009;203:113–7.
[63] Zheng Y, Balabhadrapatruni S, Masumura C, Darlington CL, Smith PF. Effects of the putative cognitive-enhancing ampakine, CX717, on attention and object recognition memory in rats. Curr. Alzheimer Res. 2011;8(8):876–82.
[64] Dehaene S, Brannon E. Space, Time and Number in the Brain. Amsterdam: Elsevier; 2011.
[65] Chen C-S. Can rats count? Nature 1967;214:15–7.

[66] Breukelaar JWC, Dalrymple-Alford JC. Timing ability and numerical competence in rats. J Exp Psychol: Animal Behav Proc 1998;24:84–97.
[67] Scarf D, Hayne H, Colombo M. Pigeons on par with primates in numerical competence. Science 2011;334:1664.
[68] Hubbard EM, Piazza M, Pinel P, Dehaene S. Interactions between number and space in the parietal cortex. Nature Revs Neurosci 2005;6:435–48.
[69] Zorzi M, Priftis K, Umiltà C. Brain damage – neglect disrupts the mental number line. Nature 2002;417:138–9.
[70] Fias W, van Dijck J-P, Gevers W. How is number associated with space? The role of working memory. In: Dehaene S, Brannon E, editors. Space, Time and Number in the Brain. Elsevier: Amsterdam; 2011. p. 133–48.
[71] Dehaene S, Cohen L. Cultural recycling of cortical maps. Neuron 2007;56: 384–98.
[72] Dehaene S. Long or linear? Distinct intuitions of the number scale in Western and Amazonian indigenous cultures. Science 2008;320:1217–20.
[73] Fischer MH, Castel AD, Dodd MD, Pratt J. Perceiving numbers causes spatial shifts of attention. Nature Neurosci 2003;6:555–6.
[74] Hartmann M, Grabherr L, Mast FW. Moving along the mental number line: Interactions between whole body motion and numerical cognition. J Exp Psychol: Human Percept Perform 2012, in press.
[75] Goddard M, Zheng Y, Darlington CL, Smith PF. Synaptic protein expression in the medial temporal lobe and frontal cortex following chronic bilateral vestibular loss. Hippocampus 2008;18:440–4.
[76] Goddard M, Zheng Y, Darlington CL, Smith PF. Monoamine transporter and enzyme expression in the medial temporal lobe and frontal lobes following chronic bilateral vestibular loss. Neurosci Lett 2008;437:107–10.