Journal of Vestibular Research 16 (2006) 75–91
IOS Press

Cognitive-vestibular interactions: A review of patient difficulties and possible mechanisms

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Received 1 December 2005
Accepted 5 October 2006

Abstract. Cognitive deficits such as poor concentration and short-term memory loss are known by clinicians to occur frequently among patients with vestibular abnormalities. Although direct scientific study of such deficits has been limited, several types of investigations do lend weight to the existence of vestibular-cognitive effects. In this article we review a wide range of studies indicating a vestibular influence on the ability to perform certain cognitive functions. In addition to tests of vestibular patient abilities, these studies include dual-task studies of cognitive and balance functions, studies of vestibular contribution to spatial perception and memory, and works demonstrating a vestibular influence on oculomotor and motor coordination abilities that are involved in the performance of everyday cognitive tasks. A growing literature on the physiology of the vestibular system has demonstrated the existence of projections from the vestibular nuclei to the cerebral cortex. The goals of this review are to both raise awareness of the cognitive effects of vestibular disease and to focus scientific attention on aspects of cognitive-vestibular interactions indicated by a wide range of results in the literature.

Keywords: Vestibular, cognitive, balance, spatial

1. Introduction

A common, but often deëmphasized, symptom of vestibular disorders is the experience of difficulties with cognitive skills such as short-term memory, concentration, arithmetic, and reading. While a complete understanding of the vestibular-cognitive connection remains elusive, studies of several types do provide evidence for a vestibular role in cognitive tasks. In addressing these cognitive deficits, it is important to distinguish between conditions of general disorientation or confusion, which could lead to specific task deficits as a secondary consequence, and specific impairments to cognitive performance. A practical issue of great significance for vestibular patients is the frequent dismissal of their symptoms as purely psychological in origin [46, 61,116,119]. The argument that cognitive and affective symptoms do not *particularly* result from vestibular injuries (viz. [44]), may encourage some physicians to downplay such symptoms among vestibular patients or even misdiagnose vestibular injury when such symptoms are a primary indicator. Thus a primary focus of this review is to collect evidence for cognitive deficits that frequently occur among patients with vestibular disorders, even in the presence of otherwise lucid and intelligent behavior.

In this review we present evidence that the cognitive-vestibular interaction is real, yet subtle. In some tests of cognitive abilities, vestibular patients perform significantly worse than normals [3,91,111]. These tests often involve the organization of extensive information or require simultaneous attention to more than one task. However, it is not the case that general cognitive impairment results from a vestibular injury. Some tests show no significant differences between vestibular patients and normals, while others show a robust deficit, but

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ISSN 0957-4271/06/$17.00

one that is identifiable in only a subset of the vestibular population.

In the following sections we review several different types of studies providing evidence for cognitive-vestibular interactions. Our primary purpose is to summarize as much evidence as is available to indicate that vestibular impairment leads to some forms of cognitive deficits. In support of a secondary hypothesis, we argue that this effect is not necessarily just indirect (difficulty of balance and orientation may draw attention away from a cognitive task), but may also reflect a direct dependence of many cognitive operations on the vestibular system. Vestibular afference, in these cases, may be used for tasks that either implicitly require information about the structure of three-dimensional space and movement, such as navigation and spatial memory (§5.1), or for a spatial strategy employed in less obviously spatial domains, such as representation of numerals on a mental "number-line" (§2.2, 5.2).

In Section 2 we review studies of the cognitive abilities of patients with vestibular and balance disorders. Although substantial evidence is presented, much of it is subjective, preliminary, or difficult to interpret due to confounding factors. Nevertheless, this section sets the stage by presenting typical difficulties and introducing a small number of studies that have attempted to directly assess the cognitive effects of vestibular disorders. Section 3 presents results from dual-task studies of cognitive and balance functions that have used both normal and vestibular-deficient subjects. Many of these studies support the non-independence of cognitive and vestibular/balance functions by demonstrating decrements in cognitive or balance performance as a result of increased difficulty in the opposing domain. In addition, these studies provide some of the best experimental evidence for deficient performance by vestibular patients on specific cognitive tasks.

Following the behavioral evidence of an effect of vestibular function on cognition provided by Sections 2 and 3, Sections 4 and 5 delve into the possible nature of the connection. Section 4 contains a brief review of the anatomical and physiological evidence for vestibulocortical projections, including a review of confirmed links to the hippocampus. These projections are not known to subserve any particular cognitive task, but they do present the likelihood that some areas of the cortex involved in standard cognitive tasks such as arithmetic receive signals of vestibular origin and could be affected by a disruption to vestibular afference. Section 5 considers the general role of the vestibular system in spatial cognition, as well as studies of hemineglect patients that demonstrate spatialization in many cognitive tasks that are not generally viewed as having a direct spatial component. Thus, Section 5 especially addresses the role of the vestibular system in contributing to spatialization of cognitive operations.

2. Clinical studies of vestibular patients

The existence of cognitive symptoms among vestibular patients, including short-term memory loss, loss of concentration, and an inability to multitask, are well attested by clinicians involved in the treatment of these patients [46,60,61,111]. Scientific literature in support of this connection is unfortunately limited by (1) the difficulty of quantifying cognitive deficits, and (2) the reluctance to address cognitive symptoms of disorders that are already routinely dismissed as purely psychological ailments. Nevertheless, cognitive problems associated with vestibular disorders have been documented by a number of studies. In this section we present evidence for the cognitive complaints of patients and for a few experimental studies that have attempted to measure specific cognitive deficits among patients. We argue that more studies of this type are called for, cautioning against oversimplified measures that fail to reveal such specific effects.

2.1. Subjective reports and measures

Subjective measures of the handicap in daily living occasioned by balance disorders and vertigo have been developed [64,118]. Among the issues identified as prevalent among such patients are difficulties with reading and concentration, restriction of mobility, and aversion to environments such as supermarket aisles [21,50, 64,118]. Self-rated severity of these cognitive symptoms has shown high intrasubject reliability and correlates well with more commonly recognized vestibular symptoms [65], as well as measures of functional ability [108]. For example, scores on the Dizziness Handicap Inventory (DHI) of Jacobson and Newman [64] have been shown to correlate with performance on platform posturography tests [65]. Nevertheless, responses to the DHI reveal facets of the handicap experienced by the patient that cannot be predicted from laboratory testing alone [65]. Likewise, the Vertigo Handicap Questionnaire (VHQ) focusses on issues such as restriction of activities and occupational difficulties in an attempt to quantify the severity of impairment from vertigo [114,118]. Scores on the VHQ are predicted by

those of the Vertigo Symptom Scale, which has been shown to dissociate the effects of organic vertigo from those of anxiety [116].

Many items included in these subjective scales have a clear cognitive component, involving conscious processes such as decision-making, orientation of attention, and memory recall. At the same time, affective responses such as dizziness, pain, and fear clearly contribute to many of the self-ratings. Thus, attention to the details of these survey results will be useful in addressing the cognitive difficulties of vestibular patients, even though the composite scores do not necessarily measure general "cognitive" functioning. What is especially of interest for this review is that the issues listed above (including reading, concentration, and short-term memory) have been correlated by the subjective scales with clinically identified vestibular disorders.

Tests of patients diagnosed with panic attacks and/or agoraphobia indicate a high instance of vestibular abnormalities (sometimes $>$80%), especially when posturography is included as an assessment tool [61,62, 109,115]. The correlation between agoraphobic symptoms and balance disorders holds even when the effects of anxiety are taken into account [109]. In studies of substantial numbers of panic patients, normals, and patients with vestibular abnormalities or hearing loss, Jacob and colleagues identified several self-rated difficulties as statistically predictive of a vestibular abnormality. These "Space and Motion Discomfort" aspects include reading in a car, looking at items on the shelf in a supermarket, travelling through a curved tunnel, or looking at lights on the side, and travelling in elevators [61]. Although these are certainly not stereotypical cognitive tasks, the results do indicate that nonclinical symptoms of vestibular dysfunction can be distinguished from secondary effects of panic and/or anxiety. This is extremely important, since anxiety without a vestibular disorder is also certain to have cognitive effects, so that it is necessary to distinguish the primary cause as either anxiety or a vestibular disorder.

2.2. Clinical and experimental test results

A small number of studies have gone further, experimentally assessing cognitive disabilities of vestibular patients in the laboratory. In this section we review results on arithmetic abilities, short-term memory, concentration, and performance in contexts of visual discord.

Risey and Briner [91] reported a specific and robust cognitive error (in backwards counting) that occurred in roughly 20% of patients presenting with vertigo. The specific error noted by the authors involved the skipping of a decade when counting backward by twos, as, for example, in the sequence "... 84, 82, **70**, 78, 76, 74, 72, **60**, 68, 66, ...". Usually these subjects did not even recognize the error when they were shown their responses in written form. In subsequent tests of forward and backward counting abilities, it was found that subjects who were identified as having the counting disorder were slower and made more errors than normals when counting backwards, even though they showed no significant decrements in counting forwards.

Although a variety of spatial and nonspatial strategies can be used for the performance of arithmetic tasks [32], we speculate that that the results of Risey and Briner indicate a deficit in spatialization, or at least reordering, of the numeric sequence. Since numerals are learned by rote in the increasing order, forward counting is relatively automatic, while backward counting requires participants to reorder this information. The ordering of information, such as seen in (forward and backward) counting, represents a basic form of spatial organization in the cognitive task (for further evidence of spatialization of counting, see §5). Normal performance on some of the simpler tasks (e.g. forward counting), far from contradicting the existence of a cognitive-vestibular connection, serves to delineate the nature of the vestibular effect. Moreover, the Risey and Briner [91] study shows that a specific cognitive effect cannot always be expected to appear as a result of all types of vestibular injury. Subjects exhibiting the counting disorder consisted almost exclusively of patients with central vestibular lesions (most likely in the brainstem), while patients with peripheral lesions (i.e. damage to the vestibular sensory organs of the inner ear) were no more likely than normals to make this error, and in fact showed normal performance on all of the arithmetic/counting tests administered.

Likewise, Andersson and colleagues [3,4] have shown that vestibular patients perform significantly worse (at least much more slowly) than normals on the task of counting backwards by steps of seven. This was true regardless of whether the counting task was performed alone or paired with balance disruption by vibratory calf stimulation as part of a dual-task design (§3).

A promising study of vestibular patient performance on specific cognitive tasks (particularly short-term and working memory) has been undertaken by Erickson and colleagues [35]. Using a group of patients with hydrops, perilymph fistulae, and/or benign paroxysmal

positional nystagmus (BPPN), Erickson et al. [35] identified several tasks on which their patient group scored significantly lower than age-matched controls. On such standard psychological measures as the Digit Span (which tests memory span by measuring the length of a sequence of random numerals that can be repeated by the subject) and the Mini Mental State Exam (which tests orientation, attention, immediate and short-term recall, language, and ability to comprehend and follow commands), average patient performance fell within the normal range. However, patients showed significantly reduced levels of performance on tests designed to measure more complex abilities, such as organizing multiple sources of information or learning new information while retaining previous items in memory. When distracted by the alternating performance of two distinct tasks (in the *Divided Attention Recall Test*), patients showed a significantly reduced ability to recall a recently presented item. In the *Logical Memory Tests*, which invited free recall of information presented verbally in prose form, patients were found to perform just as well as normals in recalling verbatim items from the passage, but showed a significantly decreased ability for recall of semantic or nonverbatim information. These tests go beyond the memory assessment of the Digit Span or Mini Mental, which merely ask the subject to remember a sequence of digits or words, instead including skills of parallel processing and semantic organization of information. In summary, the Erickson et al. study identifies specific sorts of cognitive tasks that cause significant difficulties for vestibular patients who are not generally impaired or exaggerating their symptoms, as shown by their normal performance on simple tests of short-term memory.

In a study of individuals who experienced dizziness, but who did not necessarily seek treatment from neuro-otological specialists, Yardley and colleagues [110] found strong correlations between the incidence of a diagnosis of vestibular disorder, diminished balance function as tested by computerized dynamic posturography, and the presence of psychiatric difficulties including poor concentration. Although gross vestibular abnormalities of the type that might be identified by caloric stimulation were rare, the Yardley et al. [110] results clearly indicate a connection between mild balance/vestibular problems and persistent cognitive and psychological difficulties.

Work of Bronstein and colleagues [21,22,50,96] shows that vestibular-deficient subjects can experience decreased sensitivity to visual movement or visually-induced vertigo without movement of the head, and therefore without any stimulation of the vestibular endorgans. At the same time, vestibular patients frequently show a high degree of visual dependence [50, 62] and are particularly susceptible to imbalance in conditions of visual-vestibular discord [50]. It has been noted in multiple works that patients with balance disorders commonly experience discomfort in environments with repetitive or moving visual patterns, such as those encountered in supermarkets, automobile traffic, tunnels, or aisles [21,39,61,62]. Although such difficulties cannot immediately be identified as "cognitive", difficulties in the visual domain, for even a stationary subject, go beyond the normally recognized symptoms of vestibular or balance disorders and will certainly affect cognitive skills such as reading and spatial reasoning (§5).

2.3. Future directions

Surprisingly, there has been little, if any, further effort to demonstrate the reduced cognitive capabilities of vestibular-deficient subjects experimentally (as in the preliminary data of Erickson et al.). Such studies would be challenging, since there is limited possibility of before-and-after tests of the same subject, and since cognitive abilities can be difficult to quantify. Nevertheless, it seems well worth the effort to simply match vestibular against normal subjects (controlling for age, educational level, etc.) and give experimental weight to the objective *presence* of cognitive effects between groups. Alternatively, given the high incidence of vestibular abnormalities even among "normal" subjects [62,115], it may be possible to conduct blind studies of cognitive abilities and determine a correlation with the presence of a vestibular abnormality. The difficulty here is that, since vestibular deficits are mild in these non-symptomatic subjects, cognitive effects must be expected to be less severe and more subtle; thus design of appropriate cognitive tasks becomes a priority. Although such studies might not address the deeper question of *how* vestibular function affects cognitive processes, they would at least objectively investigate whether specific cognitive abilities are diminished by a vestibular deficit. Further evidence for a vestibular-cognitive connection at the behavioral level would be of tremendous service to vestibular patients and clinicians.

Tests of cognitive abilities in patients are of course highly susceptible to conflicting factors such as lack of motivation or distraction by more overt symptoms. However, we believe that the cited studies, as well as

those to be presented in §3, show that much information can still be gained. Clinically, it seems likely that awareness of these issues often leads to subjective cognitive complaints being treated with skepticism. But there is preliminary evidence for abandoning such a stance: in a related study of a large number of patients suffering from whiplash, Radanov and colleagues [86] have shown that persistent reports of cognitive disability correlate with somatic symptoms, independently of personality traits, economic or educational status, or insurance coverage (the Swiss subjects of the Radanov et al. study did not have insurance and liability concerns comparable to those of many American patients). Damage to the vestibular system is common in whiplash, and there is certainly a high degree of correlation between the behavioral effects of the two types of injuries [43,46]. Cognitive and psychological complaints related to whiplash are likewise frequently dismissed as malingering.

There is no doubt that the symptoms of vestibular injuries can be disorienting, and that episodes of vertigo or disorientation interfere with the performance of many day-to-day activities. But are cognitive difficulties really only symptoms of symptoms? Such a conclusion is argued for in an article of Gizzi et al. [44], who found that patients with documented vestibular disorders do not score significantly differently on three measures of mental/psychological health than do patients suffering from dizziness, but without any documented vestibular injury. The authors found that level of depression or level of trauma were better predictors of self-rated handicap than vestibular diagnosis. The conclusion that this proves that the cognitive disabilities are not caused by vestibular deficits is, however, problematic, since the measures used in the study do not necessarily test cognitive abilities.

A principal measure used by the Gizzi et al. [44] study, the Dizziness Handicap Inventory (DHI) [64], is intended to measure the subject's ability to cope with daily life, rather than any specifically cognitive ability (§2.1). For example, one question used from the DHI is whether the subject avoids going out alone. Certainly the ability to go out alone is important for quality of life, but does it measure cognitive abilities? A person might avoid such activity as walking alone because of a lack of spatial memory – perhaps walking around feels just fine, but it is impossible to remember the way home. This would undeniably represent a cognitive deficit. On the other hand, a person might avoid such activity just because it brings on nausea, panic attacks, or symptoms of agoraphobia; or simply from a fear of falling over and being injured. The point is that it is no surprise that anyone with dizziness would score poorly on such a quality-of-life measure as the DHI. While individual questions from the DHI might be revealing about facets of cognitive performance, the composite score does not seem appropriate as a measure of "cognitive" ability. Our conclusion is that much more detailed study is required in order to determine *which* cognitive operations are affected by a vestibular disorder.

3. Dual-task studies of cognitive and balance/orientation functions

Several studies have experimentally investigated the connection between cognitive performance and balance function (effectively defined as the ability to limit body sway while standing) or the ability to orient in space. In these studies, cognitive tasks are paired with postural challenges such as standing on a compliant surface or orientation tasks such as maintaining a visual line in the vertical direction. The main questions are whether the postural challenge will have an effect on cognitive performance, and conversely, whether performance of the cognitive task decreases postural stability. Vestibular patients routinely perform worse than normals on both tasks, often irrespective of whether they are performed individually or together [3,87,111]. In addition to this correlation of cognitive performance with vestibular disorders, dual-task interference in patients or normal subjects can indicate a vestibular-cognitive connection. Clearly, such dual-task effects could result merely from the interference between simultaneous tasks, a relatively indirect connection; dual-task effects are frequently discussed in terms of competition for attentional resources [87,97,111]. It is also possible, however, that disruption of spatial reference, either by the postural task or a sensory disorder, may have a more direct effect on the ability to complete certain cognitive tasks, regardless of attentional resources (see also §6.2).

In general, dual-task studies can be difficult to interpret; in particular, there is no way of being certain that one has completely matched tasks of such different types for difficulty. If one task is fundamentally more difficult, or demands more attention, then it may interfere more with the other task, without proving anything about the structure of the pathways involved. This fact may account for divergent conclusions in the literature, as reviewed below. In light of this difficulty, we will

prefer, in general, simply to note that there is an effect on one task of concurrent performance of the other, when this is borne out by the data, instead of arguing that the influence is particularly in one direction.

In this section we review the results of several dual-task studies, giving especial weight to studies that used vestibular patients in addition to normal controls. The results of these experiments support our arguments both by indicating some basic cognitive tasks on which vestibular patients exhibit decreased performance and by showing that the difficulty of an orientation or balance task can affect cognitive performance. The latter result suggests functional connectivity between systems, but even if this cannot yet be verified, it should at least be noted that, if a normal subject standing on a foam surface suffers decreased arithmetic or memory skills, then it is not unlikely that the same effect will be observed in a balance-disorder patient under more natural conditions.

3.1. Cognitive/balance dual-task results

Dual-task studies that pair cognitive tasks with the requirement of maintaining standing balance are appealing, in that the balance task measures and/or simulates one of the most prominent symptoms of a vestibular disorder. A methodological drawback of such studies, however, is that a patient in fear of falling may shift almost all attention to the balance task. In itself, this would indicate situations in which patients necessarily suffer reduced cognitive performance, but it does limit any conclusions that can be drawn about a more direct dependence of the cognitive task on vestibular function.

In one dual-task study, Yardley and colleagues found that increasing the difficulty of maintenance of postural orientation (by standing on a platform that sways with the subject) increased response time and decreased accuracy on mental tasks for both vestibular patients and controls [111]. Their experiments did not demonstrate any effect on postural stability of performing the cognitive task. As the authors note, these results are consistent with the hypothesis that maintenance of balance is given "attentional priority" over cognitive operations. Just as importantly, the study shows that vestibular patients performed significantly worse than controls on several cognitive tasks, regardless of the postural conditions (sitting, standing, or destabilized by use of a posture platform). In particular, patients scored worse on speeded tasks of discrimination between even and odd numbers and determination of clockhand arrangements corresponding to a pair of numbers. The conclusion drawn by the authors is that vestibular patients may perform poorly on cognitive tasks because they devote more of a limited attentional resource to maintaining balance and postural stability.

Contrary to the Yardley et al. [111] results, Maylor and colleagues [77] have found that the postural sway of normal subjects is increased while performing a cognitive task. Using the Brooks spatial and non-spatial memory tasks, they found an increase in sway velocity during the time period in which a sequence was maintained in memory (but not while attending to the spoken stimulus). Although they did not find any postural effect on cognitive operations, one must consider that vestibular patients, who are already susceptible to greater imbalance, may be less able to accept the added postural instability caused by the performance of a cognitive task. In addition to using only normal subjects, the Maylor et al. [77] study also used different cognitive tasks from that of Yardley et al. [111].

Similarly, in a study of patients with well-compensated unilateral vestibular lesions, Redfern et al. [87] tested simple, inhibitory, and forced-choice reaction times against age-matched controls in various postural conditions (seated, standing, standing on a sway-referenced floor, or standing on a translating floor). The result were that patients had slower reaction times than controls under all conditions, and that postural sway increased similarly in all subjects when performing the reaction-time tasks [87]. Again, this study shows that cognitive and postural operations are not entirely separate. More importantly here, the results show that a basic cognitive skill is decreased in vestibular patients, even though the patients in question had no significant postural deficit, the subjects may be seated, and the cognitive task does not appear to require the use of any vestibular reflex.

Shumway-Cook et al. [97] found in a study of young and aging adults that concurrent performance of a cognitive task has a mild effect on postural stability, with the effect much larger in elderly patients with a history of falls. Contrary to their expectations, the performance of a sentence-completion task had a greater effect than a visuospatial task requiring the matching of parallel lines. Shumway-Cook and colleagues interpret all such effects in terms of "allocation of attention" (they expected the visuospatial task to use more visual attention and therefore have greater effects). However, it is possible to instead interpret their results in terms of visual contribution to balance: in the line-matching task subjects retained the screen as a visual fixation point, while in the verbal task subjects may have averted their

gaze from the screen in front of them [45]. Vestibular patients, as well as balance-impaired elderly patients, are likely to depend much more on visual fixation for balance [21,22,50]. It would be interesting to see whether the results could be reversed by placing the computer screen off to one side of the subject's midline. In addition, one must consider the possibility that articulation of a verbal response may itself interfere with balance [30].

Interestingly, other studies indicate that postural sway may not be affected by performance of a concurrent mental task in the expected way. It has been noted that both normal subjects and subjects with peripheral vestibular disorders decrease their peak amplitude of postural sway (on a stable surface) when performing a cognitive task [5,18]. Moreover, healthy elderly patients step to maintain balance at a lower threshold of center of mass displacement when in a dual-task situation [24]. It would seem from these results that humans naturally adjust their postural *strategies* when performing a concurrent cognitive task. Since patients with balance disorders have considerably less flexibility in setting their postural strategy, the dual-task situation could more easily affect balance (because an inefficient postural strategy is used) or the performance of the required cognitive task (which is suppressed in order to avoid imbalance). It would be of interest to test whether a change in postural strategy can be induced merely by indicating to the subject that a cognitive task is forthcoming.

3.2. Cognitive/orientation dual-task results: no postural imperative

As discussed above, one difficulty with the usual dual-task design (§3.1) is that the imperative of avoiding a fall may lead to a situation in which the subject devotes very little attention to the cognitive task, particularly if the subject suffers from a vestibular or balance disorder. In the two articles presented in this section, this difficulty is removed by replacing balance by an orientation task. This task is as dependent on vestibular function, but does not come weighted with the imperative of avoiding a fall.

In a subsequent article [117] the Yardley group performed a sequence of experiments pairing a mental task (backward counting) with a task requiring the identification of vertical during either passive rotation of the subject or visually induced self-motion perception using a rotating disc. Unlike normal subjects, vestibular patients in the study (excepting one patient with a complete bilateral absence of vestibular function) showed a significant effect of the "vestibular" task (identification of vertical) on their ability to perform the mental task. While the precise neurological implications of these findings remain unclear, they at least show that vestibular function and performance of spatial updating are not completely independent of cognitive tasks such as backward counting. The authors conclude that "individuals who [are] disoriented, whether because of uncompensated vestibular imbalance or experimentally induced visual-vestibular conflict, must devote attention to monitoring orientation, with a resulting detrimental impact on concurrent mental activity" [117]. Although this is a plausible explanation, it should be noted that, since the subjects did not need to maintain balance in this task, it is far less likely than in dual-task cognition and balance paradigms (§3.1) that deficits on the arithmetic task accrued solely from "attentional priority" of the orientation task.

Similarly, in earlier studies Yardley and colleagues had found that the concurrent performance of a cognitive task (backward counting, or a simple arithmetic task) could decrease the ability of normal subjects to relocate a starting point after passive rotation in the dark [112,113]. The authors take this result as evidence that updating of spatial location requires some degree of mental effort or attention (certainly some cortical resource), a commodity in lesser supply during operation of the arithmetic task. It is also possible that the arithmetic task itself requires a stable spatial framework, inhibiting the perception of inertial movement (§5).

3.3. Summary

Dual-task studies of cognitive and balance/orientation functions relate to the issues faced by vestibular patients in ordinary life, in that postural difficulties and disorientation are primary symptoms of vestibular deficits. A fairly consistent finding is that vestibular-deficient subjects perform worse on cognitive tasks such as backward counting, especially when these must be carried out in a posturally demanding or disorienting environment. Studies presented in this section show that the performance of orientation/balance tasks and cognitive tasks impact upon one another, with stronger effects generally seen among vestibular patients.

With regard to dual-task studies of normal individuals, it must be remembered that no matter how difficult the balance task may be, if cognitive difficulties experienced by vestibular patients actually result directly

from a deficit in vestibular function (rather than occurring as secondary effects of imbalance), then dual-task studies of normals cannot completely simulate the situation faced by the vestibular-deficient patient. More promising may be paradigms in which the vestibular signal is continuously altered or contradicted (as with a centrifuge or posture platform).

The results that do emerge with some certainty from dual-task studies of cognition and balance are (1) that vestibular patients generally perform worse than normals on a set of cognitive tasks including backward counting, regardless of the postural task; and (2) that the vestibular/balance and cognitive systems do not operate entirely independently of one another. Regardless of mechanism, these results are almost certain to imply greater cognitive difficulties for vestibular-deficient patients in any situation that taxes the balance or orientation systems.

4. The vestibular cortex

If vestibular signals are to have a direct influence on cognition, then one expects to find evidence for neural pathways by which vestibular signals are passed to the cerebral cortex. Evidence for such vestibulo-cortical projections of course falls short of a complete explanation for functional effects on cognition, but it should at least give pause to any *a priori* argument that the vestibular system's usual characterization in terms of reflexes and balance should exclude a role in cognition. Section 4.1 presents a brief review of the evidence for vestibulo-cortical maps, focussing on human and primate studies. Section 4.2 focusses on vestibular projections to the hippocampus, which may be especially significant for deficits in in spatial navigation and memory skills.

4.1. Vestibulo-cortical maps

Although the "vestibular cortex" does not enjoy a distinction comparable to that of the somatosensory or visual cortices, recent anatomical and physiological evidence shows that there are multiple regions of the human cerebral cortex that receive afferent signals from the vestibular system. Anatomically, these projections appear primarily to be (at least) disynaptic via the thalamus [38]. Vestibularly-activated regions of the cortex include, at the least, areas of the somatosensory and parietal cortices, as well as a posterior insular region corresponding to the primate parietoinsular vestibular cortex (PIVC) [1,6,13,15,34,38,101,106]. In addition, areas showing vestibular-related activity have been found in the premotor frontal lobe and visual cortex [38,73]. Many of the identified neurons receive convergent visual, vestibular, and somatosensory afferents.

Cortical regions receiving vestibular projections have been identified using both single-neuron recording in primates [1,19,51,67–69,94] and functional imaging or PET scans of humans [13,34,56,101,105]. The latter findings in humans, which were obtained primarily using caloric stimulation of vestibular canals, have been largely confirmed using galvanic vestibular stimulation (GVS), though the identified regions (unsurprisingly) did not overlap completely [73].

In addition to finding activation in the temporoparietal junction (corresponding to primate PIVC) and central sulcus (primate region 3aV), Lobel and colleagues found activation of the intraparietal sulcus, a region corresponding to primate area 2v [73,101]. The intraparietal sulcus is a region known to be involved in multimodal coordinate transformations and the representation of space [2]. The ventral intraparietal area (VIP) in monkeys receives strong vestibular activity [19,67–69, 94]. In monkeys as in humans, this parietal area is implicated in hemineglect [40,102]. Additionally, the intraparietal sulcus has been identified as a principal area involved in arithmetic and counting tasks [98], perhaps hosting anb "amodal representation of quantity" [31, 32,36]. This overlap of vestibularly driven cortical areas with those involved in arithmetic may correlate behaviorally with the spatialization of arithmetic operations that has been observed in studies of hemineglect patients (§5.2).

Guldin and Grüsser [51] identified the PIVC as the core region in a well-defined vestibular cortical system in the squirrel monkey; a system that also contains parts of the somatosensory areas 3a and 2v. They noted that, as their results were generally confirmed by studies of both rhesus [26,95] and macaque [47,48] monkeys, it is natural to expect a similar network in humans. Projections back to the vestibular complex are attested to by the effect on vestibular reflexes, such as the vestibulo-ocular reflex (VOR), of lesions to the cerebral cortex [38].

The human studies of Emri et al. [34] and Bottini et al. [14] both used PET scanning in conjunction with caloric stimulation of the vestibular canals, and concur in identifying the insular homologue of the PIVC, consisting of somatosensory area SII and the Retroinsular cortex, as most clearly activated by vestibular path-

ways. This region of the multisensory parietal cortex appears to receive both canal and otolith signals [15]. In a subsequent study, Bottini and colleagues [13] have identified the insula, retroinsular cortex, temporoparietal junction, and somatosensory area II as responsive to both caloric stimulation of the inner ear and neck muscle vibration. By comparing normal subjects with cerebellar patients with no apparent vestibular function, the Emri et al. [34] study provides stronger evidence for a specifically vestibular contribution to PIVC activation, dissociating this contribution from that of a concurrent somatosensory stimulus. Bottini and colleagues [13] argue that the regions of the cortex identified in their study contribute to a representation of egocentric space that is independent of sensory modality.

Brandt and colleagues [16] have shown using PET and fMRI techniques that the human PIVC and the occipital visual cortex are mutually inhibitory. In other words, vestibular stimulation both stimulates the vestibular cortex and inhibits the visual cortex, while a visual motion stimulus inhibits the PIVC. As discussed by the authors, this mutual inhibition may resolve visual-vestibular conflicts at the cortical level, effectively silencing the weaker signal. Visual-vestibular inhibition helps explain such phenomena as visually-induced vection and could also account for some of the observed visual-dependence effects seen in vestibular patients (§2.2). For example, a person with a weaker cortical vestibular representation, although able to function in the absence of vision, may find their perceptions abnormally dominated by the visual stimulus in a conflict situation [21,50].

A recent report of Indovina et al. [56] shows that the cortical network activated by vestibular stimulation, particularly the human homologue of the PIVC, is also activated by a visual task in which the stimulus depicts an object apparently accelerated by the force of gravity. Activation in this network was not seen when the object's acceleration was inconsistent with the operation of gravity. This result is highly significant, in that it demonstrates recruitment of the extended vestibular system for the performance of a visually-oriented cognitive task. The anatomical area of interest is not entirely, or even primarily, a visual area. Moreover, the results appears to indicate that the vestibular system can contribute invariants of movement in physical space to purely visual information for the performance of cognitive tasks, since in this case a cortical area known to receive vestibular signals is recruited specifically for a visual task that involves recognition of the effects of gravity, even though the task apparently involves no more vestibular *sensation* than similar visual tasks.

Although more research needs to be done, recent studies have definitively identified areas of the cerebral cortex that are responsive to vestibular stimulation. These areas are involved in at least some cognitive operations and appear to be particularly involved in spatialization of cognitive operations, consistent with the vestibular system's role in the perceptual structuring of extrapersonal space. In fact, the studies cited in this section indicate a clear physiological and anatomical substrate for our hypothesis of a direct contribution of vestibular signals to cognition. Much work remains to determine the functional role of these projections; however, this "hard" evidence for a connection between vestibular and cortical systems should be a vital stimulus to further research into behavioral and clinical cross-effects between the cognitive and balance/vestibular domains.

4.2. Vestibular projections to the hippocampus

Especially important for the effects of a vestibular lesion on memory will be projections from the vestibular system to the hippocampus. Animal studies have confirmed the existence of polysynaptic vestibular pathways to this brain region [99], and activation of the hippocampus by vestibular stimulation has also been documented in humans [105]. In a recent study of Brandt et al. [17], it was even shown that patients with bilateral vestibular loss suffered significant atrophy of the hippocampal formation (a 16.9% decrease in hippocampal volume relative to controls). This is especially significant for a discussion of cognition, since it is also known that the hippocampus plays a prominent role in some forms of memory, particularly spatial memory [74,78]. In fact, in the Brandt et al. [17] study, hippocampal atrophy in bilateral vestibular patients was accompanied by impairments to spatial memory (see also §5.1).

Recent studies have shown that electrical stimulation of the guinea pig vestibular labyrinth induce long-latency electrical activity in the hippocampus, regardless of the site of stimulation (canal, utricle, or saccule) [29,53]. Horii et al. [55] similarly showed that stimulation of the rat medial vestibular nucleus caused increased firing rate in individual hippocampal neurons, particularly complex-spiking 'place cells'. Although the pathways for this activation remain somewhat unclear, these studies clearly indicate a vestibular-hippocampal projection [99]. Neurochemical effects of a peripheral vestibular lesion can include a reduction of hippocampal NMDA receptor expression [72]. Since these receptors are important for memory, learn-

ing, and long-term potentiation, this result may help explain learning and memory deficits associated with vestibular damage [99].

The hippocampus is thought to be especially involved in spatial navigation and spatial memory. Studies of rats have identified the hippocampus as integral to the construction and memory of spatial maps and the ability to navigate through known environments [25, 81,99], with several studies indicating a strong effect of hippocampal damage on performance of such spatial tasks as the Morris water maze [20,42,80]. Similarly, behavioral experiments have shown that animals with peripheral vestibular damage perform poorly on various learning and memory tasks [99]. For example, Stackman and Herbert [100] found that rats with bilateral vestibular lesions performed well on a spatial task in lighted conditions, but that their performance was deficient in the dark. It is expected in these latter studies that the effect on performance is via hippocampal pathways.

Jacobs and Schenk [63] have found evidence for the existence of two types of spatial maps in the hippocampus: "sketch maps" that indicate relative positions of objects within a localized area and "gradient maps" that encode position and movement relative to an externally defined vector. In this formulation, vestibular sensation and function is especially relevant for the formation and updating of the gradient map, particularly through path integration [63].

In studies of humans using functional MRI, the hippocampus has been found to reorganize in accordance with the demands of spatial memory [74] and to show particular activation in a task that involves the navigation between remembered spatial locations [70]. Maguire et al. [74] have found increased volume of the posterior hippocampi of London taxi drivers (who must master an enormous amount of information concerning relative spatial locations), corresponding to the length of time spent in this occupation. Moreover, the same group have found that outstanding memorizers frequently apply spatial strategies, even to nonspatial memory tasks [75]. Combined with the results of Brandt et al. [17] on hippocampal atrophy in vestibular patients, these results provide strong evidence for an effect of vestibular disorders (via the hippocampus) on spatial memory and the ability to navigate (even mentally) through a spatially organized domain.

5. Vestibular function in spatial cognition

It is widely agreed that the vestibular system plays a prominent role in the cognitive functions of spatial perception, spatial memory, and perception of movement [8,52,57,66,79]. This section briefly reviews contributions of the vestibular system to spatial memory and perception, including a few effects that need not involve any direct vestibular sensation.

5.1. *Spatial perception, spatial memory, and perception of movement*

Cortical networks receiving multisensory stimuli, including the vestibular sensation of rotational or translational acceleration of the head, can integrate motion to estimate the magnitude of a completed rotation or translation, or even the shape of a travelled path. While such path integration may be less vital in well marked environments like a street grid, inadequacies in this respect could easily lead to the types of agoraphobic behavior commonly seen in vestibular patients [62]. Spatial *memory*, which would seem to be a more purely cognitive function, also appears to be diminished by vestibular loss (§4.2).

In a task of spatial memory [12], normal subjects could make an accurate saccade back to an original fixation point after whole body rotation without visual reference, whereas labyrinthine-defective subjects [79] and patients with lesions in the parietal or prefrontal cortices or the supplemental eye field were unable to do so [58,82,103]. Brookes et al. [23] showed that normal subjects could accurately reposition themselves with a joystick after passive rotation in the dark, while this ability was lacking in patients with bilateral or acute unilateral vestibular loss. Likewise, studies of normal subjects have shown that rotation of a mental map is facilitated by actual rotation, which stimulates vestibular and proprioceptive systems. Both Presson and Montello [85] and Rieser et al. [89] found that the ability to point to memorized locations with closed eyes is diminished to a much greater extent by an imagined self-rotation than by an actual self-rotation. These results clearly point to nonvisual influences on the contents of spatial memory.

The perceived magnitude of linear motion is contributed to and perhaps dominated by the otolith signal, even when vision is present [52]. In fact, while travelled distance can be estimated from a (virtual) visual signal alone, the accuracy of this estimation is greatly facilitated if the visual stimulus corresponds to a motion with constant acceleration above the vestibular threshold [88]. Even though vision is generally thought to register velocity of motion, this result shows that prop-

erties of the vestibular system structure the perception of self-motion in any sensory domain.

Combined storage of linear and angular movements leads to the ability for path integration or reconstruction of a travelled trajectory [9,10,59]. While the ability to reconstruct a travelled path is far from perfect in an unstructured visual environment, general features of the path are recorded when normal semicircular and otolithic afferents are available, even in the absence of vision or proprioceptive clues [59]. On the other hand, serious errors can accrue when the observer is presented with visual flow alone [9,10].

The contribution of the otolithic sensation of gravity to spatial memory is indicated by a study of Watt [107], who found that astronauts made larger errors in pointing to memorized target locations in microgravity than on earth. As noted in the study, such an effect could result either from a deficit in the map of target locations held in memory or from a deficit in the ability to track the location of one's own limbs in space [107]. However, the predominance of a deficit in memory for target location was shown by the fact that the effect of microgravity on pointing accuracy was substantially higher when subjects were not allowed to view the target array between trials (in both cases subjects were required to keep their eyes shut during extension and retraction of the arm) [107]. It is especially significant in these results that, since the subject did not move during the experiment, perception of verticality was not *a priori* necessary for spatial memory of visual targets. Nevertheless, alterations in vestibular sensation seem to have affected a map of allocentric space.

Finally, in a study of patients with bilateral vestibular loss, Brandt et al. [17] found that patients displayed significant performance deficits on a virtual Morris water maze task, which required navigation through a virtual environment to a learned target, but from an uncued start location. This was in spite of the fact that the patients showed no significant decrement in the ability to navigate to a visual target, or in general memory as measured by more standardized tests [17]. In this case spatial memory and navigation deficits coincided with atrophy of the hippocampus, indicating a neurological pathway for the for the behavioral effect (§4.2). Importantly, in this study vestibular loss decreased spatial navigation performance even on a purely visual task in which there is no vestibular stimulation.

Spatial memory and path integration are not usually conscious processes, but certainly contribute to cognitive abilities to follow directions or remain aware of one's position in open or visually repetitive environments such as those found in malls, supermarkets, or parking lots. The likely overreliance on visual cues by vestibular patients in these environments may lead to an increased sense of insecurity and even agoraphobic avoidance.

5.2. Hemineglect studies

A simple form of disturbance in spatial cognition is seen in hemineglect patients, who exhibit diminished awareness of stimuli arising spatially contralateral to the side of a cortical lesion. While neglect of events and objects in extrapersonal space is familiar, effects of hemineglect can encompass deficits in motor, sensory, cognitive, or attentional function [37,40,102]. Studies of neglect patients have the potential to demonstrate spatial organization in cognitive processes, since there will be pronounced deficits in the subject's attention to the affected side of any information coded with left-right spatial structure. In addition, it has been shown that perceptual and cognitive deficits of hemineglect patients can be ameliorated by stimulation of the vestibular organs [41,93]. Thus hemineglect studies, while dealing with a neurological disorder fundamentally different from that presented by vestibular loss, demonstrate both spatialization in many cognitive processes and an influence of vestibular function on cognitive ability.

In a study of Rinaldi et al. [90], for example, neglect subjects with right brain damage were less able to locate the stressed word in a short spoken sentence when that word occurred near the beginning of the sentence. Similarly, Hillis and Caramazza [54] and Baxter and Warrington [7] have found that neglect patients make more spelling errors at the beginning or end of a word, depending upon the side of neglect (e.g. damage to the right hemisphere causes more errors near the beginning of the word). These results indicate a left-right organization of even spoken language for speakers of English (which is likely to be reversed in readers of languages written right-to-left). Such results are well-known when the sentence is presented visually as text [27], but are more surprising for verbal communication, since in this case the left-right spatialization is entirely internal. Dehaene et al. [33] have shown a similar spatial organization of numeric processing. In their experiments, normal subjects were asked to press a button with their left hand in response to odd numerals and a button with their right hand in response to even numerals. The finding was that for small numerals (those at the left end of a "mental number line"),

response was quicker with the left hand; responses to large numerals were quicker when the right hand was used.

Likewise, Zorzi and colleagues [120] have given evidence for use of a mental number line in certain arithmetic tasks by showing that neglect patients systematically shift the midpoint of a numerical interval when asked to bisect it. In the Zorzi et al. [120] study subjects were merely presented with two integers and asked to find the midpoint of the interval, a task which is not transparently spatial; nevertheless, their bias matched that of neglect subjects asked to bisect a physical line [76]. It should be noted that the subjects scored in the normal range on tests of subtraction and number comparison, arithmetic tasks that are not susceptible to the same sort of spatial error. The Zorzi et al. [120] results indicate that finding the midpoint of an interval is accomplished by representing the interval spatially, and that the deficits on this task resulted from the particular spatial component of its execution.

Caloric stimulation of the vestibular canals can lessen the severity of hemineglect, including its cognitive symptoms [41,92,93]. In addition, the severity of hemineglect is affected by electrical stimulation of neck muscles [49], reorientation of the gravitational vertical [83], and optokinetic stimulation [104]; all of these influences are likely to be mediated, at least in part, through the vestibular nuclei. In the study of Guariglia and colleagues [49], it was shown that asymmetries in drawing and in memory for a familiar location, commonly associated with hemineglect, were decreased by stimulation of neck muscles on the side ipsilateral to the neglect. Interestingly, stimulation on the opposite side improved certain types of performance on the non-neglect side. This latter fact suggests that stimulation of vestibular pathways may increase spatial awareness and functioning independently of the presence of hemineglect.

These studies of hemineglect indicate that certain types of cortical (cognitive) functions depend upon vestibular afference. Moreover, the functions in question are not restricted to awareness of extrapersonal space (a recognized vestibular function). Neglect symptoms are also present with regard to mental images, and even in this case caloric stimulation has been shown to have an effect. Rode and Perenin [92], for example, showed that caloric stimulation on the side of neglect increased the ability to recall items on the affected side of a visual image held in memory (subjects were asked to visualize a map of France and name towns, which were classified as either on the left or right side of the map). While the Rode and Perenin study still focussed on a patently "spatial" imagery function, the studies of Rinaldi et al. [90] and Zorzi et al. [120] show that even verbal and numerical tasks can be spatialized (see above).

The results on hemineglect patients provide strong evidence that (1) common cognitive operations such as arithmetic, sentence comprehension, and short-term memory can be highly spatialized (certainly there are nonspatial strategies that may sometimes be employed); and (2) vestibular signals can contribute to the ability to organize information spatially. Although the cognitive effects of a vestibular disorder are likely to be different, and perhaps not as severe as those of hemineglect, we may suppose that any disruption of vestibular function or spatial organization will have related (if more subtle) effects on cognitive operations.

6. Summary and future directions

In this review we have collected results from a number of different types of studies indicating a link between vestibular function and certain types of cognitive abilities. In addition to the observations of clinicians working with patients with vestibular and balance disorders, we find evidence in dual-task studies of posture and cognition, studies of spatial cognition and spatial memory, and the spatial aspects of cognitive functions revealed through studies of hemineglect patients. On the physiological side, a growing literature on the existence of a human vestibular-cortical system, and on its activation in spatial tasks, provides great impetus for an exploration of vestibular contributions to cognitive tasks.

Two important issues for future research into the vestibular-cognitive effect are (1) what are the particularly cognitive operations affected by the vestibular disorder? and (2) what is the mechanism by which a change in vestibular function affects cognition? Both of these questions are of high relevance for the treatment of vestibular patients. In order for cognitive difficulties to be properly diagnosed and treated, the affected operations need to be rigorously defined. Once this is achieved, analysis of patient data can be examined for the consistent occurrence of such difficulties among patients. Nevertheless, greater acceptance of cognitive sequelae of vestibular disorders, and the development of treatment strategies for these symptoms, will require some understanding of the mechanisms by which vestibular dysfunction inhibits the performance

of cognitive tasks. The determination of both appropriate cognitive tasks and vestibular-cognitive mechanisms are likely to require much further research.

6.1. Indirect consequences of a vestibular disorder

Although the strength of direct vestibular influences on cognition remains a subject for continuing research, indirect consequences of a vestibular disorder undeniably restrict the ability of a vestibular-deficient individual to carry out everyday cognitive tasks. In practice, even the requirements of a desk job involve enough movement of the head and torso that any decrement in vestibular reflexes will lead to errors, delays, and frustration. Moreover, these subtle decrements in function can continue even long after the patient has clinically "recovered" from the peripheral vestibular abnormality [46].

Normal reading, for example, involves a slow steady head movement from side to side, combined with a concurrent sequence of eye saccades [71]. During fixation of an individual word, the vestibulo-ocular reflex (VOR) is therefore involved in keeping the gaze focussed. While many patients recover normal VOR gain constants, Black et al. [11] have found a more frequent long-term reduction in the VOR time constant in ototoxic patients. Either of these parameters could have an impact on the complex task of reading. Vestibular patients often compensate by steadying the head and moving the gaze with eye-only saccades [28,84], but this may be out of the question if required to read signs while walking or driving.

Even if pure mental operations were possible without vestibular spatialization, a lack of normal vestibular function is therefore likely to inhibit the ability to acquire or respond to the information required for these operations. Residual effects of a vestibular abnormality may have subtle effects on oculomotor control and orientation abilities that cause repeated delays and inaccuracy in the performance of everyday tasks. Conversely, further research may identify cognitive diagnostic tests for persistent mild vestibular dysfunction that is undetectable by ordinary clinical assessment.

6.2. Direct consequences: Limited attentional resources versus direct vestibular input

While the vestibular system clearly contributes to such cognitive activities as spatial perception and memory (one can't remember a travelled path, for example, unless one can accurately detect one's own motion in the first place), it is less clear how vestibular deficiencies can directly impact the performance of cognitive tasks, such as counting, arithmetic, or short-term memory and recall of visually or verbally presented information, that need not *a priori* require spatial updating. Nevertheless, such deficits are routinely observed in patients, and the results of studies cited in this review suffice to show that they are not completely independent of the vestibular deficiency. There are two ways to explain such a connection. First, spatial disorientation (regardless of cause) may draw attention away from cognitive tasks, decreasing the level of performance (§3). Alternatively, it is likely that the human brain (unlike a computer algorithm) does in fact carry out memory and recall operations within a relational framework that resembles that of physical space, and that this spatial representation is constructed in very much the same way as the representation of extrapersonal physical space (viz. §5). Consequently, many of these cognitive operations would depend directly on vestibular function for their optimal performance. Although there is probably some truth to the first explanation, we consider it important to explore the second, since it posits a more primary connection between vestibular and cognitive functions.

6.3. Conclusion

Although vestibular patients routinely indicate difficulties with such cognitive skills as concentration, short-term memory, and reading, there is little direct quantitative data on the cognitive effects of vestibular injuries. Nevertheless, these types of decrements do show up in more general assessments of well-being and psychological health (§2), as well as in the cognitive performance seen in many dual-task studies (§3). Much more research needs to be done.

From a physiological perspective, the existence of cognitive-vestibular interactions is supported by the existence of neuronal projections between the vestibular centers in the brainstem and the cerebral cortex (§4). It is well established that the vestibular system is critical in the execution of spatial navigation and spatial memory tasks, both of which certainly have a cognitive/cortical component (§5). This deficit can perhaps be explained in terms of a cortical representation of external space and the body's movement through it: deficits in the vestibular sensory system detract from the ability to accurately update this representation.

In future, tests of the *cognitive* abilities of vestibular patients (as opposed to their general well-being or psychological health) will need to focus on specific tasks

such as reading, arithmetic, navigation, or short-term memory tasks. Several such tasks have been developed for use in dual-task studies (§3). Rather than argue for or against a general cognitive impairment associated to vestibular disorders, researchers should begin to delimit the more specific cognitive impairments symptomatic of each type of vestibular malady.

It is our hope that this review will both (1) contribute to a wider acceptance of the natural association of cognitive symptomology with vestibular disorders, and (2) indicate issues for further research into cognitive-vestibular connections. As discussed above, it seems to us almost undeniable that vestibular loss or dysfunction must detract from the ability to perform many ordinary cognitive tasks. We believe, however, that this relationship is only the tip of the iceberg, that vestibular function may be shown by future research to contribute vital spatial structure for a wide variety of cognitive processes.

Acknowledgements

The research for this article was supported by a grant from the Research Advisory Committee of the Legacy Research Center and a grant from the Medical Research Foundation of Portland, Oregon. We wish to thank Drs. Robert J Grimm and Benson Schaeffer for offering valuable advice on the preparation of the manuscript. Also, we wish to acknowledge the access to unpublished data and manuscripts in addition to personal experience provided by Drs. F. Owen Black and Kenneth R. Erickson.

References

[1] S. Akbarian, O.J. Grüsser and W.O. Guldin, Corticofugal connections between the cerebral cortex and the brainstem vestibular nuclei in the macaque monkey, *J Comp Neurol* **339**(3) (1994), 421–437.

[2] R.A. Andersen, Encoding of Intention and Spatial Location in the Posterior Parietal Cortex, *Cereb Cortex* **5**(5) (1995), 457–469.

[3] G. Andersson, J. Hagman, R. Talianzadeh, A. Svedberg and H.C. Larsen, Dual-Task Study of Cognitive and Postural Interference in Patients with Vestibular Disorders, *Otol Neurotol* **24** (2003), 289–293.

[4] G. Andersson, J. Hagman, R. Talianzadeh, A. Svedberg and H.C. Larsen, Effect of cognitive load on postural control, *Brain Res Bull* **58** (2002), 135–139.

[5] G. Andersson, L. Yardley and L. Luxon, A Dual-task Study of Interference Between Mental Activity and Control of Balance, *Am J Otol* **19** (1998), 632–637.

[6] C.D. Balaban and J.F. Thayer, Neurological bases for balance-anxiety links, *J Anxiety Disorders* **15** (2001), 53–79.

[7] D.M. Baxter and E.K. Warrington, Neglect Dysgraphia, *J Neurol Neurosurg Psychiatry* **46**(12) (1983), 1073–1078.

[8] A. Berthoz, The role of inhibition in the hierarchical gating of executed and imagined movements, *Brain Res Cogn Brain Res* **3**(2) (1996), 101–113.

[9] R.J.V. Bertin and A. Berthoz, Visuo-vestibular interaction in the reconstruction of travelled trajectories, *Exp Brain Res* **154** (2004), 11–21.

[10] R.J.V. Bertin, I. Israël and M. Lappe, Perception of two-dimensional, simulated ego-motion trajectories from optic flow, *Vision Res* **40** (2000), 2951–2971.

[11] F.O. Black, S. Pesznecker and V. Stallings, Permanent Gentamicin Vestibulotoxicity, *Otol Neurotol* **25** (2004), 559–569.

[12] J. Bloomberg, G. Melvill Jones, B. Segal, S. McFarlane and J. Soul, Vestibular-contingent voluntary saccades based on cognitive estimates of remembered vestibular information, *Adv Otorhinolaryngol* **41** (1988), 71–75.

[13] G. Bottini, H.-O. Karnath, G. Vallar, R. Sterzi, C.D. Frith, R.S.J. Frackowiak and E. Paulesu, Cerebral representations for egocentric space: Functional-anatomical evidence from caloric vestibular stimulation and neck vibration, *Brain* **124** (2001), 1182–1196.

[14] G. Bottini, R. Sterzi, E. Paulesu, G. Vallar, S.F. Cappa, F. Erminio, R.E. Passingham, C.D. Frith and R.S. Frackowiak, Identification of the central vestibular projections in man: a positron emission tomography activation study, *Exp Brain Res* **99** (1994), 164–169.

[15] T. Brandt and M. Dieterich, The Vestibular Cortex: Its locations, functions, and disorders, *Ann NY Acad Sci* **871** (1999), 293–312.

[16] T. Brandt, S. Glasauer, T. Stephan, S. Bense, T.A. Yousry, A. Deutschlander and M. Dieterich, Visual-Vestibular and Visuovisual Cortical Interaction: New Insights from fMRI and PET, *Ann NY Acad Sci* **956** (2002), 230–241.

[17] T. Brandt, F. Schnautzer, D.A. Hamilton, R. Brüning, H.J. Markowitsch, R. Kalla, C. Darlington, P. Smith and M. Strupp, Vestibular loss causes hippocampal atrophy and impaired spatial memory in humans, *Brain* **128** (2005), 2732–2741.

[18] S.G. Brauer, M. Woollacott and A. Shumway-Cook, The Interacting Effects of Cognitive Demand and Recovery of Postural Stability in Balance-Impaired Elderly Persons, *J Gerontol: Med Sci* **56A**(8) (2001), M489–M496.

[19] F. Bremmer, F. Klam, J.-R. Duhamel, S. Ben Hamed and W. Graf, Visual-Vestibular Interactive Responses in the Macaque Ventral Intraparietal Area (VIP), *Eur J Neurosci* **16** (2002), 1569–1586.

[20] N.J. Broadbent, L.R. Squire and R.E. Clark, Spatial memory, recognition memory, and the hippocampus, *Proc Natl Acad Sci USA* **101** (2004), 14515–14520.

[21] A.M. Bronstein, Vision and vertigo: Some visual aspects of vestibular disorders, *J Neurol* **251**(4) (2004), 381–387.

[22] A.M. Bronstein, Visual vertigo syndrome: clinical and posturography findings, *J Neurol Neurosurg Psychiatry* **59**(5) (1995), 472–476.

[23] M.A. Brookes, M.A. Gresty, T. Nakamura and T. Metcalfe, Sensing and controlling rotational orientation in normal subjects and patients with loss of labyrinthine function, *Am J Otol* **14**(4) (1993), 349–351.

[24] L.A. Brown, A. Shumway-Cook and M.H. Woollacott, Attentional demands and postural recovery: the effects of aging, *J Gerontol Med Sci* **54A** (1999), M165–M171.

[25] N. Burgess, E.A. Maguire and J. O'Keefe, The human hippocampus and spatial and episodic memory, *Neuron* **35** (2002), 625–641.
[26] U. Büttner and U.W. Buettner, Parietal cortex area 2v neuronal activity in the alert monkey during natural vestibular and optokinetic stimulation, *Brain Res* **153**(2) (1978), 392–397.
[27] A. Caramazza and A.E. Hillis, Spatial representation of words in the brain implied by studies of a unilateral neglect patient, *Nature* **346**(6281) (1990), 267–269.
[28] I.S. Curthoys and G.M. Halmagyi, Vestibular compensation: a review of the oculomotor, neural, and clinical consequences of unilateral vestibular loss, *J Vestib Res* **5** (1995), 67–107.
[29] P.C. Cuthbert, D.P. Gilchrist, S.L. Hicks, H.G. MacDougall and I.S. Curthoys, Electrophysiological evidence for vestibular activation of the guinea pig hippocampus, *Neuroreport* **11** (2000), 1443–1447.
[30] M.C. Dault, L. Yardley and J.S. Frank, Does articulation contribute to modifications of postural control during dual-task paradigms? *Brain Res Cogn Brain Res* **16**(3) (2003), 434–440.
[31] S. Dehaene, G. Dehaene-Lambertz and L. Cohen, Abstract representations of numbers in the animal and human brain, *Trends Neurosci* **21** (1998), 355–361.
[32] S. Dehaene, N. Molko, L. Cohen and A.J. Wilson, Arithmetic and the brain, *Curr Op Neurobiol* **14** (2004), 218–224.
[33] S. Dehaene, S. Bossini and P. Giraux, The mental representation of parity and numerical magnitude, *J Exp Psychol Gen* **122** (1993), 371–396.
[34] M. Emri, M. Kisely, Z. Lengyel, L. Balkay, T. Marian, L. Miko, E. Berenyi, I. Sziklai, L. Tron and A. Toth, Cortical projection of peripheral vestibular signaling, *J Neurophysiol* **89** (2003), 2639–2646.
[35] K.R. Erickson, M. DeWeese and A. Simons, A specific syndrome of memory impairment in patients with vestibular disorder: selective acquisition and retrieval deficits. Unpublished manuscript.
[36] W. Fias, J. Lammertyn, B. Reynvoet, P. Dupont and G.A. Orban, Parietal representation of symbolic and nonsymbolic magnitude, *J Cogn Neurosci* **15** (2003), 47–56.
[37] A.F. Fuchs and J.O. Phillips, Association cortex, in: *Textbook of physiology*, H.D. Patton, A.F. Fuchs, B. Hille, A.M. Scher and R. Steiner, eds, Saunders, Philadelphia, 1989, pp. 663–692.
[38] K. Fukushima, Corticovestibular interactions: anatomy, electrophysiology, and functional considerations, *Exp Brain Res* **117** (1997), 1–16.
[39] J.M. Furman and R.G. Jacob, A clinical taxonomy of dizziness and anxiety in the otoneurological setting, *J Anxiety Disorders* **15** (2001), 9–26.
[40] D. Gaffan and J. Hornak, Visual neglect in the monkey: Representation and disconnection, *Brain* **120** (1997), 1647–1657.
[41] G. Geminiani and G. Bottini, Mental representation and temporary recovery from unilateral neglect after vestibular stimulation, *J Neurol Neurosurg Psychiatry* **55** (1992), 332–333.
[42] P.E. Gilbert and R.P. Kesner, Role of the rodent hippocampus in paired-associate learning involving associations between a stimulus and a spatial location, *Behav Neurosci* **116** (2002), 63–71.
[43] R. Gimse, C. Tjell, I.A. Bjorgen and C. Saunte, Disturbed eye movements after whiplash due to injuries to the posture control system, *J Clin Exp Neuropsychol* **18**(2) (1996), 178–186.
[44] M. Gizzi, M. Zlotnick, K. Cicerone and E. Riley, Vestibular Disease and Cognitive Dysfunction: No Evidence for a Causal Connection, *J Head Trauma Rehabil* **18**(5) (2003), 398–407.
[45] A.M. Glenberg, J.L. Schroeder and D.A. Robertson, Averting the gaze disengages the environment and facilitates remembering, *Memory and Cognition* **26**(4) (1998), 651–658.
[46] R.J. Grimm, W.G. Hemenway, P.R. Lebray and F.O. Black, The Perilymph Fistula Syndrome Defined in Mild Head Trauma, *Acta Otolaryngol Suppl* **464** (1989), 1–40.
[47] O.J. Grüsser, M. Pause and U. Schreiter, Localization and responses of neurons in the parieto-insular vestibular cortex of the awake monkeys (*Macaca fascicularis*), *J Physiol* **430** (1990), 537–557.
[48] O.J. Grüsser, M. Pause and U. Schreiter, Vestibular neurons in the parieto-insular cortex of monkeys (*Macaca fascicularis*): visual and neck receptor responses, *J Physiol* **430** (1990), 559–583.
[49] C. Guariglia, G. Lippolis and L. Pizzamiglio, Somatosensory stimulation improves imagery disorder in neglect, *Cortex* **34**(2) (1998), 233–241.
[50] M. Guerraz, L. Yardley, P. Bertholon, L. Pollak, P. Rudge, M.A. Gresty and A.M. Bronstein, Visual vertigo: symptom assessment, spatial orientation and postural control, *Brain* **124**(Pt 8) (2001), 1646–1656.
[51] W.O. Guldin and O.J. Grüsser, Is there a vestibular cortex? *Trends Neurosci* **21**(6) (1998), 254–259.
[52] L.R. Harris, M. Jenkin and D.C. Zikowitz, Visual and non-visual cues in the perception of linear self motion, *Exp Brain Res* **135** (2000), 12–21.
[53] S.L. Hicks, D.P.D. Gilchrist, P. Cuthbert and I.S. Curthoys, Hippocampal field responses to direct electrical stimulation of the vestibular system in awake or anesthetised guinea pigs, *Proc Aust Neurosci Soc* **15** (2004), 87.
[54] A.E. Hillis and A. Caramazza, Spatially specific deficits in processing graphemic representations in reading and writing, *Brain Language* **48**(3) (1995), 263–308.
[55] A. Horii, N. Russell, P.F. Smith, C.L. Darlington and D. Bilkey, Vestibular influences on CA1 neurons in the rat hippocampus: an electrophysiological study in vivo, *Exp Brain Res* **155** (2004), 245–250.
[56] I. Indovina, V. Maffei, G. Bosco, M. Zago, E. Macaluso and F. Lacquaniti, Representation of Visual Gravitational Motion in the Human Vestibular Cortex, *Science* **308** (2005), 416–419.
[57] I. Israël, M. Fetter and E. Koenig, Vestibular perception of passive whole-body rotation about horizontal and vertical axes in humans: goal-directed vestibulo-ocular reflex and vestibular memory-contingent saccades, *Exp Brain Res* **96** (1993), 335–346.
[58] I. Israël, S. Rivaud, A. Berthoz and C. Pierrot-Deseilligny, Cortical control of vestibular memory-guided saccades, *Ann NY Acad Sci* **656** (1992), 472–484.
[59] Y.P. Ivanenko, R. Grasso, I. Israël and A. Berthoz, The contribution of otoliths and semicircular canals to the perception of two-dimensional passive whole-body motion in humans, *J Physiol* **502**(1) (1997), 223–233.
[60] R.G. Jacob and J.M. Furman, Psychiatric consequences of vestibular dysfunction, *Curr Opin Neurol* **14**(1) (2001), 41–46.
[61] R.G. Jacob, J.M. Furman and J.M. Perel, Panic, Phobia, and Vestibular Dysfunction, in: *Vestibular Autonomic Regulation*, B.J. Yates and A.D. Miller, eds, CRC Press Inc., 1996.

[62] R.G. Jacob, J.M. Furman, J.D. Durrant and S.M. Turner, Panic, Agoraphobia, and Vestibular Dysfunction, *Am J Psychiatry* **153** (1996), 503–512.
[63] L.F. Jacobs and F. Schenk, Unpacking the Cognitive Map: The Parallel Map Theory of Hippocampal Function, *Psychol Rev* **110**(2) (2003), 285–315.
[64] G.P. Jacobson and C.W. Newman, The Development of the Dizziness Handicap Inventory, *Arch Otolaryngol Head Neck Surg* **116** (1990), 424–427.
[65] G.P. Jacobson, C.W. Newman, L. Hunter and G.K. Balzer, Balance Function Test Correlates of the Dizziness Handicap Inventory, *J Am Acad Audiol* **2** (1991), 253–260.
[66] R. Jürgens, T. Boß and W. Becker, Estimation of self-turning in the dark: comparison between active and passive rotation, *Exp Brain Res* **128** (1999), 491–504.
[67] F. Klam, Head movement-related signals and the representation of space in parietal cortex: an electrophysiological study with awake behaving monkeys. Ph.D. dissertation, College de France – Univ. Paris VI, Paris, France, 2004.
[68] F. Klam and W. Graf, Vestibular Response Kinematics in Posterior Parietal Cortex Neurons of Macaque Monkeys, *Eur J Neurosci* **18** (2003), 995–1010.
[69] F. Klam and W. Graf, Vestibular Signals of Posterior Parietal Cortex Neurons during Active and Passive Head Movements in Macaque Monkeys, *Ann NY Acad Sci* **1004** (2003), 271–282.
[70] D. Kumaran and E.A. Maguire, The Human Hippocampus: Cognitive Maps or Relational Memory? *J Neurosci* **25**(31) (2005), 7254–7259.
[71] C. Lee, Eye and head coordination in reading: roles of head movement and cognitive control, *Vision Res* **39** (1999), 3761–3768.
[72] P. Liu, J. King, Y. Zheng, C.L. Darlington and P.F. Smith, Long-term changes in hippocampal NMDA receptor subunits following peripheral vestibular damage, *Neurosci* **117** (2003), 965–970.
[73] E. Lobel, J.F. Kleine, A. Leroy-Willig, P.F. Van de Moortele, D. Le Bihan, O.J. Grüsser and A. Berthoz, Cortical areas activated by bilateral galvanic vestibular stimulation, *Ann NY Acad Sci* **871** (1999), 313–323.
[74] E.A. Maguire, D.G. Gadian, I.S. Johnsrude, C.D. Good, J. Ashburner, R.S.J. Frackowiak and C.D. Frith, Navigation-related structural change in the hippocampi of taxi drivers, *PNAS* **97**(8) (2000), 4398–4403.
[75] E.A. Maguire, E.R. Valentine, J.M. Wilding and N. Kapur, Routes to remembering: the brains behind superior memory, *Nat Neurosci* **6** (2003), 90–95.
[76] J.C. Marshall and P.W. Halligan, When right goes left: an investigation of line bisection in a case of visual neglect, *Cortex* **25**(3) (1989), 503–515.
[77] E.A. Maylor, S. Allison and A.M. Wing, Effects of spatial and nonspatial cognitive activity on postural stability, *Brit J Psychol* **92** (2001), 319–338.
[78] B.L. McNaughton, C.A. Barnes, J.L. Gerard, K. Gothard, M.W. Jung, J.J. Knierim, H. Kudrimoti, Y. Qin, W.E. Skaggs, M. Suster and K.L. Weaver, Deciphering the hippocampal polyglot: the hippocampus as a path integration system, *J Exp Biol* **199** (1996), 173–185.
[79] T. Nakamura and A. Bronstein, The perception of head and neck angular displacement in normal and labyrinthine-defective subjects. A quantitative study using a remembered saccade technique, *Brain* **118** (1995), 1157–1168.
[80] J. O'Keefe, Do hippocampal pyramidal cells signal non-spatial as well as spatial information? *Hippocampus* **14** (1999), 148–152.
[81] J. O'Keefe and L. Nadel, *The hippocampus as a cognitive map*, Oxford: Oxford UP, 1978.
[82] C. Pierrot-Deseilligny, I. Israel, A. Berthoz, S. Rivaud and B. Gaymard. Role of the different frontal lobe areas in the control of the horizontal component of memory-guided saccades in man, *Exp Brain Res* **95** (1993), 166–171.
[83] L. Pizzamiglio, G. Vallar and F. Doricchi, Gravitational inputs modulate visuospatial neglect, *Exp Brain Res* **117**(2) (1997), 341–345.
[84] T. Pozzo, A. Berthoz, L. Lefort and E. Vitte, Head stabilization during various locomotor tasks in humans. II. Patients with bilateral peripheral vestibular deficits, *Exp Brain Res* **82** (1991), 97–106.
[85] C.C. Presson and D.R. Montello, Updating after rotational and translational body movements: coordinate structure of perspective space, *Perception* **23**(12) (1994), 1447–1455.
[86] B.P. Radanov, G. DiStefano, A. Schnidrig and M. Sturzenegger, Common whiplash: psychosomatic or somatopsychic? *J Neurol Neurosurg Psychiatry* **57** (1994), 486–490.
[87] M.S. Redfern, M.E. Talkowski, J.R. Jennings and J.M. Furman, Cognitive influences in postural control of patients with unilateral vestibular loss, *Gait Posture* **19**(2) (2004), 105–114.
[88] F.P. Redlick, M. Jenkin and L.R. Harris, Humans can use optic flow to estimate distance of travel, *Vision Res* **41** (2001), 213–219.
[89] J.J. Rieser, A.E. Garing and M.F. Young, Imagery, action and young children's spatial orientation: It's not being there that counts, it's what one has in mind, *Child Development* **45** (1994), 1043–1056.
[90] C. Rinaldi, P. Marangolo and L. Pizzamiglio, Between language and space: a cross-domain interaction, *Neuroreport* **14**(10) (2003), 1381–1383.
[91] J. Risey and W. Briner, Dyscalculia in Patients with Vertigo, *J Vestib Res* **1** (1990), 31–37.
[92] G. Rode and M.T. Perenin, Temporary remission of representational hemineglect through vestibular stimulation, *Neuroreport* **5**(8) (1994), 869–872.
[93] N.D. Schiff and M. Pulver, Does vestibular stimulation activate thalamocortical mechanisms that reintegrate impaired cortical regions? *Proc R Soc London B* **266** (1999), 421–423.
[94] A. Schlack, K.-P. Hoffmann and F. Bremmer, Interaction of Linear Vestibular and Visual Stimulation in the Macaque Ventral Intraparietal Area (VIP), *Eur J Neurosci* **16** (2002), 1877–1886.
[95] D.W.F. Schwarz and J.M. Fredrickson, Rhesus monkey vestibular cortex: a bimodal primary projection field, *Science* **172** (1971), 280–281.
[96] J. Shallo-Hoffmann and A.M. Bronstein, Visual motion detection in patients with absent vestibular function, *Vision Res* **43**(14) (2003), 1589–1594.
[97] A. Shumway-Cook, M. Woollacott, K.A. Kerns and M. Baldwin, The Effects of Two Types of Cognitive Tasks on Postural Stability in Older Adults With and Without a History of Falls, *J Gerontol: Med Sci* **52A**(4) (1997), M232–M240.
[98] O. Simon, J.F. Mangin, L. Cohen, D. Le Bihan and S. Dehaene, Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe, *Neuron* **33**(3) (2002), 475–487.
[99] P.F. Smith, A. Horii, N. Russell, D.K. Bilkey, Y. Zheng, P. Liu, D.S. Kerr and C.L. Darlington, The effects of vestibular

lesions on hippocampal function in rats, *Prog Neurobiol* **75** (2005), 391–405.
[100] R.W. Stackman and A.M. Herbert, Rats with lesions of the vestibular system require a visual landmark for spatial navigation, *Behav Brain Res* **128** (2002), 27–40.
[101] M. Suzuki, H. Kitano, R. Ito, T. Kitanishi, Y. Yazawa, T. Ogawa, A. Shiino and K. Kitajima, Cortical and subcortical vestibular response to caloric stimulation detected by functional magnetic resonance imaging, *Cogn Brain Res* **12** (2001), 441–449.
[102] L. Swan, Unilateral Spatial Neglect, *Phys Ther* **81** (2001), 1572–1580.
[103] J. Tropper, G. Melvill Jones, J. Bloomberg and H. Fadlallah, Vestibular perceptual deficits in patients with parietal lobe lesions, *Preliminary study. Acta Otolaryngol* (*Stockh*) *[Suppl]* **481** (1991), 528–533.
[104] G. Vallar, C. Guariglia, L. Magnotti and L. Pizzamiglio, Optokinetic stimulation affects both vertical and horizontal deficits of position sense in unilateral neglect, *Cortex* **31**(4) (1995), 669–683.
[105] E. Vitte, C. Derosier, Y. Caritu, A. Berthoz, D. Hasboun and D. Soulie, Activation of the hippocampal formation by vestibular stimulation: a functional magnetic resonance imaging study, *Exp Brain Res* **112** (1996), 523–526.
[106] C. de Waele, P.M. Baudonniere, J.C. Lepecq, P. Tran Ba Huy and P.P. Vidal, Vestibular projections in the human cortex, *Exp Brain Res* **141**(4) (2001), 541–551.
[107] D.G. Watt, Pointing at memorized targets during prolonged microgravity, *Aviat Space Environ Med* **68**(2) (1997), 99–103.
[108] S.L. Whitney, D.M. Wrisley, K.E. Brown and J.M. Furman, Is Perception of Handicap Related to Functional Performance in Persons with Vestibular Dysfunction? *Otol Neurotol* **25**(2) (2004), 139–143.
[109] L. Yardley, J. Britton, S. Lear, J. Bird and L. Luxon, Relationship between balance system function and agoraphobic avoidance, *Behav Res Ther* **33** (1995), 435–439.
[110] L. Yardley, J. Burgneay, I. Nazareth and L. Luxon, Neuro-otological and psychiatric abnormalities in a community sample of people with dizziness: a blind, controlled investigation, *J Neurol Neurosurg Psychiatry* **65**(5) (1998), 679–684.
[111] L. Yardley, M. Gardner, A. Bronstein, R. Davies, D. Buckwell and L. Luxon, Interference between postural control and mental task performance in patients with vestibular disorder and healthy controls, *J Neurol Neurosurg Psychiatry* **71** (2001), 48–52.
[112] L. Yardley, M. Gardner, N. Lavie and M. Gresty, Attentional demands of perception of passive self-motion in darkness, *Neuropsychologia* **37**(11) (1999), 1293–1301.
[113] L. Yardley and M. Higgins, Spatial updating during rotation: the role of vestibular information and mental activity, *J Vestib Res* **8**(6) (1998), 435–442.
[114] L. Yardley, L.M. Luxon and N.P. Haacke, A longitudinal study of symptoms, anxiety and subjective well-being in patients with vertigo, *Clin Otolarygol* **19**(2) (1994), 109–116.
[115] L. Yardley, L.M. Luxon, W. Lear, J. Britton and J. Bird, Vestibular and posturographic test results in people with symptoms of panic and agoraphobia, *J Audiol Med* **3** (1994), 48.
[116] L. Yardley, E. Masson, C. Verschuur, N. Haacke and L. Luxon, Symptoms, anxiety and hadicap in dizzy patient: development of the vertigo symptom scale, *J Psychosom Res* **36**(8) (1992), 731–741.
[117] L. Yardley, D. Papo, A. Bronstein, M. Gresty, M. Gardner, N. Lavie and L. Luxon, Attentional demands of continuously monitoring orientation using vestibular information, *Neuropsychologia* **40**(4) (2002), 373–383.
[118] L. Yardley and J. Putman, Quantitative analysis of factors contributing to handicap and distress in vertiginous patients: a questionnaire study, *Clin Otolaryngol Allied Sci* **17**(3) (1992), 231–236.
[119] L. Yardley and M.S. Redfern, Psychological factors influencing recovery from balance disorders, *J Anxiety Disorders* **15** (2001), 107–119.
[120] M. Zorzi, K. Priftis and C. Umilta, Brain damage: neglect disrupts the mental number line, *Nature* **417** (2002), 138–139.