Cognitive Requirements for Vestibular and Ocular Motor Processing in Healthy Adults and Patients with Unilateral Vestibular Lesions

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Abstract

■ This study investigated the role of cognition in the vestibulo-ocular reflex (VOR) and ocular pursuit using a dual-task paradigm in patients with unilateral peripheral vestibular loss and healthy adults. We hypothesized that cognitive resources are involved in successful processing and integration of vestibular and ocular motor sensory information, and this requirement would be greater in patients with vestibular dysfunction. Sixteen well-compensated patients with surgically confirmed absent unilateral peripheral vestibular function and 16 healthy age- and sex-matched controls underwent seven combinations of vestibular-only, visual-only, and visual–vestibular stimuli while performing three different information processing tasks. Visual–vestibular stimuli included a semicircular canal and an otolith stimulus provided through seated chair rotations; fixation on a laser target and sinusoidal smooth pursuit while still; and fixation on a head-fixed laser target during chair rotations. The information processing tasks were three different auditory reaction time (RT) tasks: (1) simple RT, (2) disjunctive RT, and (3) choice RT. Our results showed increases in RTs in both patients and controls under all vestibular-only stimulation conditions and during ocular pursuit. Patients showed greater increases in RTs during vestibular stimulation and the more complex disjunctive and choice RT tasks. No differences between the groups were found during the visual-only or visual–vestibular interaction conditions. These results reveal interference between vestibulo-ocular processing and a concurrent RT task, suggesting that the VOR and the ocular motor system are dependent upon cognitive resources to some extent, and thus, are not fully automatic systems. We speculate that this interference with cognition occurs as a result of the sensory integration required for resolving inputs from multiple sensory streams. The particularly large decrement in information processing task performance of the patients compared with controls during vestibular stimulation suggests that compensation for unilateral vestibular loss requires continued cognitive resources. ■

INTRODUCTION

Interactions between the vestibulo-ocular and ocular motor systems are critical for detecting changes in motion and maintaining target fixation across a broad range of stimuli. The vestibulo-ocular reflex (VOR) has been well studied and, until recently (Furman, Muller, Redfern, & Jennings, 2003b; Yardley, Papo, et al., 2002; Yardley, Gardner, Lavie, & Gresty, 1999), has generally been considered automatic (i.e., free from the need for cognitive resources). However, patients with vestibular dysfunction often report mental fatigue, disorientation, and an inability to concentrate on cognitive tasks (Yardley, Burgneay, & Nazareth, 1998). Vestibular laboratory reports lend objective support to this assertion as it has been noted that simple ''alerting'' tasks tend to change the dynamics of the nystagmus response induced by caloric irrigation and rotational stimulation (Jacobson, Newman, & Kartush, 1993). This change typically manifests as a decrease in nystagmus dysrhythmia and an increase in quick component nystagmus generation. Thus, there is clinical and empirical evidence suggesting an interaction between higher cognitive processes and the VOR and ocular motor systems. However, this interaction remains poorly understood.

Generally, patients with peripheral unilateral vestibular loss are able to compensate for their vestibular insult such that their initial complaints of disequilibrium, disorientation, and generalized cognitive deficits tend to abate over time. Yet, it is unclear what role, if any, cognitive resources play in this compensatory process and maintaining compensation. One recent study suggests that cognitive resources do play an ongoing role (Redfern, Talkowski, Jennings, & Furman, 2004). Redfern, Talkowski, et al. (2004) investigated the impact of cognition on postural control using dual-task paradigms in well-compensated patients with surgically confirmed unilateral vestibular lesions. They found significant interference between cognitive tasks and postural control in both patients and healthy control subjects; this interference was particularly strong in the patients. It also appeared that the demand for

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cognitive resources may extend beyond postural control. Redfern, Talkowski, et al. suggested that the site of action may be at the sensory integration level (i.e., that resolving multiple sensory signals for spatial orientation required additional cognitive resources in patients with compensated unilateral vestibular lesions). The study presented here is an outgrowth from these findings. Postural control is multisensory process requiring integration of visual, proprioceptive, and vestibular sensory information. The purpose of the present study was to determine if the cognitive requirements seen in postural control are a result, in part, of interactions between higher cognitive resources and the vestibular system. Further, do patients with partial vestibular loss have increased requirements for those cognitive resources?

Dual-task experiments have been used to probe the sharing of cognitive resources under many conditions. In a dual-task paradigm, two tasks are performed concurrently and interference between the two is interpreted as a measure of shared resources. For example, numerous dual-tasking experiments have shown that postural control tasks and cognitive tasks interfere with each other by combining standing and walking balance tasks with mental arithmetic (Brown, Shumway-Cook, & Woollacott, 1999; Stelmach, Zelaznik, & Lowe, 1990), visuospatial tasks (e.g., Andersson, Yardley, & Luxon, 1998; Kerr, Condon, & McDonald, 1985), reaction time (RT) tasks (e.g., Redfern, Talkowski, et al., 2004; Redfern, Jennings, Martin, & Furman, 2001; Lajoie, Teasdale, Bard, & Fleury, 1993), word recall (e.g., Lindenberger, Marsiske, & Baltes, 2000), and verbal response tasks (Dault, Geurts, Mulder, & Duysens, 2001; Yardley, Gardner, et al., 1999). Dual-task interference has been found in many of these conditions, and researchers have suggested this interference is a result of cognitive resource requirements in standing and walking balance. Of particular interest to the current investigation are our past findings of increased interference in a secondary RT task during induced postural instability through a sway-referenced platform (Redfern, Talkowski, et al., 2004; Redfern, Jennings, et al., 2001). Sway referencing utilizes a rotating platform to mimic rotation about the ankles, thus reducing proprioceptive feedback and requiring increased reliance on the visual and vestibular systems to maintain stability (Nashner, Shupert, Horak, & Black, 1989). We interpreted the findings of interference during sway referencing to represent an increased cognitive requirement in visual–vestibular sensory integration during standing balance. In the present study, we employed this established dual-task paradigm to investigate potential interference between cognition and vestibulo-ocular function that may extend beyond postural control.

There are several studies that suggest some cognitive component to vestibulo-ocular function. In a series of dual-tasking studies using seated rotations as the primary task, Yardley, Papo, et al. (2002) and Yardley and Higgins (1998) found increased dual-task interference in a secondary arithmetic task when subjects were rotated and required to monitor their orientation. Another dual-task study assessing RTs during rotations found decreases in secondary task performance during visual fixation of a laser target during rotations, suggesting some increase in cognitive resource allocation during visual–vestibular interaction and visual suppression of the VOR (Yardley, Gradner, et al., 1999). A study of seated rotations and ocular pursuit in elderly subjects and healthy controls (Furman, Muller, et al., 2003b) also revealed dual-task interference during VOR stimulation. Furman, Muller, et al. (2003b) found increases in RTs during seated chair rotations in the dark and during VOR fixation, but no RT differences between the two conditions. The Furman et al. study further found dramatic increases in RTs during sinusoidal smooth pursuit above that of both vestibular-only and visual–vestibular interaction with no corresponding changes in pursuit accuracy. Interpretation of the significance of these findings has been difficult, as VOR suppression is generally thought to occur through a combination of visual suppression of the VOR via the brainstem and pursuit cancellation in opposition to the VOR via the cerebellum (see Leigh & Zee, 1999 for review) Thus, although the studies to date regarding vestibular-only stimulation without visual inputs found interference with secondary task performance, the cognitive resource requirements in suppressing the VOR remain unclear.

This study was performed to further define the role of cognitive resources in vestibulo-ocular and visuo-ocular motor processing by examining healthy controls and patients with absent unilateral vestibular function. The experimental design was used to address three questions:

1. Are cognitive resources required for successful vestibular and ocular motor processing?
2. Does suppression of the VOR require cognitive resources? If so, is this requirement analogous or different between VOR fixation and ocular pursuit?
3. Are there differences in the requirements for cognitive resources between patients with unilateral vestibular loss and healthy controls during vestibulo-ocular and visuo-ocular processing? In particular, does compensation for unilateral vestibular loss require increased cognitive resources?

RESULTS

Information Processing Task Performance

Table 1 summarizes the experimental conditions for this study and Table 2 provides the details of the statistical analyses. Figure 1 shows RT data for each information processing task and visual–vestibular condition combination for both patients and controls. A three-way analysis of variance with information processing task and

Table 1. Visual–Vestibular Conditions

VVC	*Vestibular*	*Visual*	*Stimulus*
Still/Dark	None	Dark	Baseline no movement
Still/Fix	None	Fixation	Visual fixation
Still/Pursue	None	Pursuit	Ocular pursuit
EVAR/Dark	EVAR	Dark	Semicircular canal
EVAR/Fix	EVAR	Fixation	VOR suppression
OVAR/Dark/CW	OVAR	Dark	Otolith—Ipsilesional/Contralesional
OVAR/Dark/CCW	OVAR	Dark	Otolith—Ipsilesional/Contralesional

This table defines the experimental conditions used, including visual–vestibular combinations (VVC), vestibular stimuli (EVAR and OVAR), visual stimuli, and intended stimulus. CW = clockwise rotation for control subjects; CCW = counterclockwise rotation for control subjects.

visual–vestibular condition as within-subject factors and group as a between-subjects factor was performed. The overall results of this analysis revealed significant main effects of information processing task ($p < .0001$) and visual–vestibular condition ($p < .0001$), but no overall group effect ($p = .20$) (see Table 2). There was a significant interaction of group and information processing task ($p = .03$); patient RTs significantly increased above controls as the complexity of the information processing task increased: simple RT ($p = .75$), dysjunctive RT ($p = .08$), and choice RT ($p < .0001$). Note that this effect was seen in the baseline Still/Dark condition. There was also a significant interaction of group and visual–vestibular condition ($p = .035$). Other interactions were not significant.

Analyses were conducted to address each specific hypothesis in this experiment. To accomplish these comparisons, we separated experimental conditions into vestibular-only, visual-only, and visual–vestibular interaction categories. To determine the impact of the visual–vestibular stimuli on information processing task performance for each hypothesis independent of baseline performance, RTs during the visual–vestibular conditions were normalized. We normalized the data by subtracting the RTs for the baseline Still/Dark from each of the other conditions for each patient and control subject for each information processing task. Although all subjects were rotated during the off-vertical condition both clockwise and counterclockwise, we found no consistent effects of direction of rotation. Thus, these conditions were collapsed into a single tilted rotation condition for analyses and graphs.

Effects of Vestibular Stimulation on Information Processing

To test the hypothesis that cognitive interference occurs during concurrent vestibular processing, analyses of the vestibular-only conditions (rotation in the dark) were carried out on the normalized RTs. The vestibular-only conditions consisted of a semicircular canal stimulus through earth vertical axis rotation (EVAR/Dark) and an otolith stimulus through off-vertical axis rotation (OVAR/Dark). The main effects of group ($p = .009$) and information processing task ($p = .004$) were significant (Figure 2, Table 2). There was no overall visual–vestibular condition effect ($p = .38$), indicating that canal and otolith stimulation in the dark have the same effect on RTs for both groups. There was a significant interaction of group and information processing task ($p = .025$), with patients showing a greater decrement in task performance during the disjunctive RT and choice RT tasks than the simple RT task. Other interactions were not significant.

Effects of Visual and Visual–Vestibular Stimulation on Information Processing

For the purpose of determining cognitive resource requirements during ocular pursuit, and comparing this requirement with that of visual suppression of the VOR, we tested the effects of sinusoidal smooth pursuit and VOR fixation on information processing task performance. To accomplish this, we compared fixation on a laser target while still (Still/Fixation), ocular pursuit (Still/Pursuit), and fixation during earth vertical axis rotation (EVAR/Fixation) for the normalized RTs. The main effects of information processing task ($p = .008$) and visual–vestibular condition ($p < .0001$) were significant. There was no significant difference between the groups ($p = .59$), nor were there any significant interactions effects (Figure 3). Post hoc comparisons showed significant differences ($p < .01$) among the three visual–vestibular conditions. The longest normalized RTs were found in the Still/Pursuit condition, followed by EVAR/Fixation, then Still/Fixation. Normalized RTs during the Still/Fixation condition were significantly greater than zero. The normalized RTs were longer for the choice RT and disjunctive RT tasks compared to the simple RT condition ($p < .01$), but were not significantly different

Table 2. Analysis of Variance Results

Variables	*df*	*F Ratio*	*Prob > F*
(a) All Data			
Group	1	1.73	.199
IPT	2	439.99	<.0001
VVC	5	38.03	<.0001
Group × IPT	2	3.80	.028
Group × VVC	5	2.48	.035
IPT × VVC	10	0.51	.881
(b) Normalized Vestibular-Only			
Group	1	7.79	.009
IPT	2	6.20	.004
VVC	1	0.78	.383
Group × IPT	2	3.93	.025
Group × VVC	1	2.26	.143
IPT × VVC	2	0.60	.549
(c) Normalized Visual–Vestibular Interactions			
Group	1	0.294	.592
IPT	2	5.22	.008
VVC	2	52.93	<.0001
Group × IPT	2	0.632	.535
Group × VVC	4	0.160	.850
IPT × VVC	4	0.481	.749

Statistical analysis results for the main effects and interactions for group (patients, controls), information processing task (IPT), and visual–vestibular combination (VVC) on the logarithmically transformed RTs for the overall analysis (a) as well as the normalized RTs for the specific vestibular and visual–vestibular combinations (b,c).

between choice RT and disjunctive RT (p = .14). Thus, there is a dual-task effect of visual stimulation and visual–vestibular interaction on RTs. Ocular pursuit creates a greater dual-task interference compared to fixation alone (Still/Fixation) and fixation during rotation (EVAR/Fixation).

DISCUSSION

This study assessed the role of cognitive resources in visual–vestibular processing through analysis of secondary RT task performance during vestibulo-ocular, visual-only, and combined visual–vestibular stimulation in well-compensated patients with unilateral vestibular loss and healthy age-matched controls. RTs were greater during vestibular stimulation and during ocular pursuit

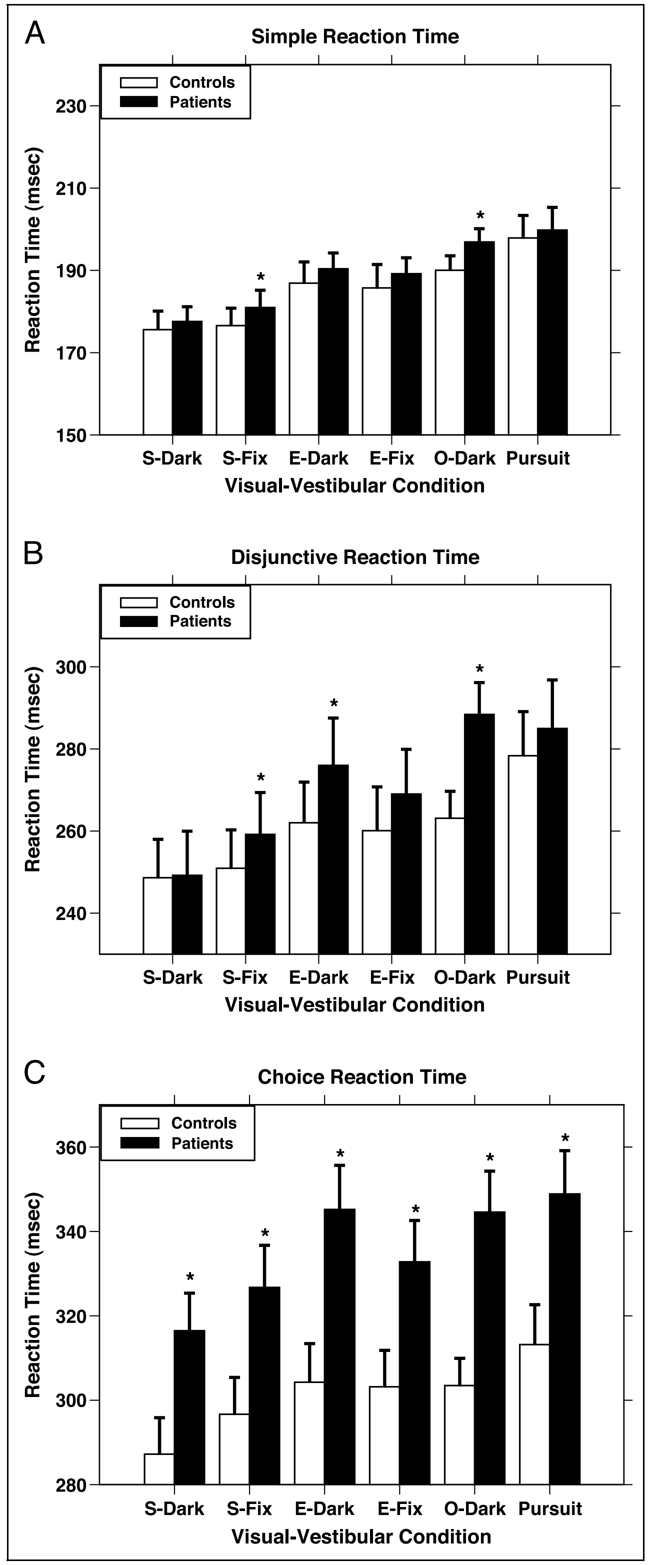

Figure 1. RTs during all visual–vestibular combinations. (A) Simple RT, (B) disjunctive RT, and (C) choice RTs for each of the seven visual–vestibular combinations (S = Still, E = EVAR, O = OVAR). The "OVAR" condition includes off-vertical axis rotation in both clockwise and counterclockwise directions in all figures. RTs are given in milliseconds (msec) and error bars represent standard errors. (*) indicates a significant increase in RTs in patients as compared with the control population.

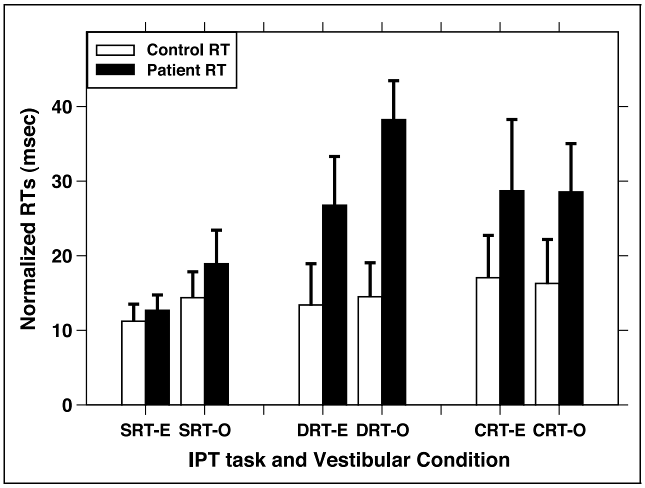

Figure 2. Normalized RTs (RT − $RT_{Still/Dark}$) during vestibular stimulation. Normalized reaction times for the vestibular-only stimulations (E = EVAR/dark, O = OVAR/dark) across all three RT tasks: simple reaction time (SRT), disjunctive reaction time (DRT), and choice reaction time (CRT). RT increases above the baseline (still/dark) RTs are given in milliseconds (msec) and error bars represent standard errors.

compared to a seated baseline condition. The vestibular stimulation (EVAR and OVAR) conditions had a significantly greater effect on the patients compared to the controls, particularly for the more complex RT tasks. Ocular pursuit and fixation tasks created increased RTs compared to baseline similarly for both the patients and controls.

We hypothesized that cognitive resources were required for successful processing and integration of visual and vestibular sensory information. The results support the hypothesis, revealing a consistent decrement in information processing task performance during conditions requiring the VOR in healthy adults and patients. This finding in healthy controls is consistent with reports by Furman, Muller, et al. (2003b), Yardley, Papo, et al. (2002), Yardley, Gradner, et al. (1999), Yardley and Higgins, (1998) of decreased performance in a secondary cognitive task during seated chair rotations in the dark. This study extends these previous findings during semicircular canal stimulation through EVAR by also documenting analogous interference during otolith ocular processing. This effect is likely to be driven by a similar mechanism to that during semicircular canal stimulation, given similar neurophysiology between semicircular canal–ocular and otolith–ocular reflexes. This idea is also supported by findings of both caloric irrigation and galvanic stimulation affecting activity in the vestibular cortical area, suggesting that stimuli to both reflexes reach cortical levels. Although the Furman, Muller, Redfern, and Jennings (2003a) study did not find consistent interference during otolithic stimulation, they did report decreases in task performance in their young control population during OVAR. We attribute the more robust effect of OVAR rotation on task performance here as compared with Furman, Muller, et al. (2003a) to an increase in the magnitude of otolithic stimulation, that is, a twofold increase in rotational velocity (30°/sec vs. 60°/sec constant velocity rotation), and a 10° increase in off-vertical axis tilt.

We also found a significant interaction of group and vestibular stimulation, as patients with absent unilateral vestibular function showed increased interference in task performance during both semicircular canal and otolith stimulus above that of healthy controls. This interference was greatest during the disjunctive RT and choice RT tasks as compared to the simple RT task. These results imply that actions of the VOR interact with cognitive tasks and are not fully automatic. The increase of this effect in our patient population as the task difficulty increased may implicate sensory integration as a key ingredient in this higher cognitive influence. The interference seen here in patients suggests an even stronger requirement of cognitive resources for sensory integration in the presence of a unilateral vestibular deficit. The patient population used in this study was well compensated, suggesting that the interference is not due to ongoing symptoms directly, but rather is associated with an ongoing central process to maintain compensation.

Our design sought to further define the role of cognitive processes during VOR fixation, and the potential impact of unilateral vestibular loss on this relationship. The results showed that visual fixation without any vestibular stimulation increased RTs. Thus, simple fixation on a target seems to require some minimal level of cognitive resources. When rotation was added, requiring

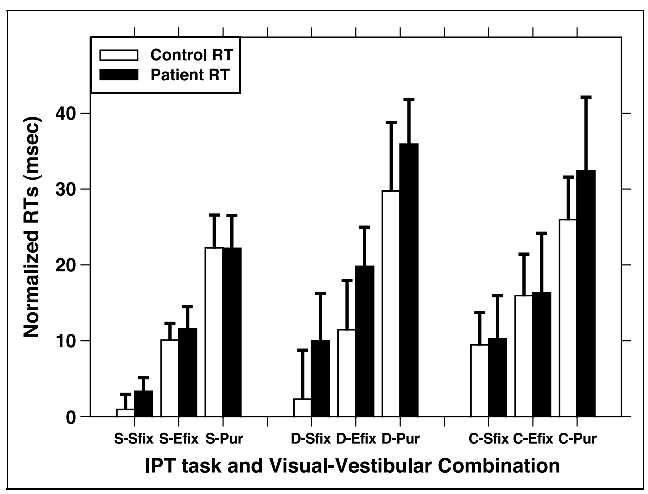

Figure 3. Normalized RTs (RT − $RT_{Still/Dark}$) during visual–vestibular stimuli. Normalized RTs for the visual–vestibular stimulations (Sfix = Still/Fixation, Efix = EVAR/Fixation, Pur = Still/Pursuit) across all three RT tasks: simple reaction time (S), disjunctive reaction time (D), and choice reaction time (C). RT increases above the baseline still/dark RTs are given in milliseconds (msec) and error bars represent standard errors.

VOR suppression, an increased cognitive input was required. This was true at the same level for patients and controls, indicating that vestibular health was not a factor in simple fixation or VOR fixation. Our results are somewhat similar to those of Yardley, Gradner, et al. (1999), who found a marked increase in secondary task performance during VOR suppression above that of simple fixation and rotation in the dark. Here, we report confirmation of the findings of cognitive interference during visual suppression of the VOR, however, we find this interference to be similar to or less than that of VOR stimulation alone.

Our results during ocular pursuit agree with Furman, Muller, et al. (2003a), who also found unexpectedly large increases in RTs during ocular pursuit. When taken together across the 40 healthy subjects in the Furman study and our population of 32 subjects, with each subject performing 192 trials across three information processing tasks, we conclude that ocular pursuit of a predictable target interacts with cortical processes and is not an automatic function. Furman, Muller, et al. (2003b) scrutinized eye movements during the pursuit task and found no evidence of changes in the accuracy or dynamics of horizontal pursuit during the information processing tasks. Kathmann et al. (1999) also found no resulting changes in pursuit accuracy during a distracting secondary task. From a practical perspective, there may be a prioritization of the necessity to pursue a moving target in space, leading to corresponding decreases in execution of simultaneous tasks. This explanation would be similar to the ''posture-first'' strategy employed during postural control dual-task paradigms, in which subjects prioritize stability during postural challenge and concomitant decreases are found in secondary task performance (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2003).

With regard to comparisons of the mechanisms involved in VOR-fixation suppression (i.e., VOR suppression and pursuit-mediated VOR cancellation), we found that ocular pursuit led to dramatic increases in RTs as compared to fixation with or without rotation. This was equally true for patients and controls. Thus, although we found evidence for cognitive resource requirements in VOR fixation, we find these requirements to be significantly less than those involved in ocular pursuit. We hypothesized that if VOR fixation was accomplished through a combination of VOR suppression and pursuit-mediated VOR cancellation, we would find similar interference for both pursuit and VOR fixation. Our failure to find such similarities suggests that visual fixation of the VOR may be a result of VOR suppression at the brainstem/reflexive level rather than pursuit cancellation of the VOR.

Baseline RTs (Still/Dark) were found to be significantly longer for the patients compared to the controls for the choice RT task. In our previous dual-task study investigating patients with vestibular loss during postural challenge, we found a similar decrement in information processing performance in the patient group during more challenging tasks, particularly those that included a requisite decision component (Redfern, Talkowski, et al., 2004). This was true even during the baseline conditions. Taken together there appears to be a generalized information processing deficit when patients with unilateral vestibular dysfunction are required to perform a cognitive task consisting of multiple response possibilities. We speculate that this deficit represents an ongoing cognitive requirement to maintain compensation for a chronic loss of unilateral vestibular processing. The increased cognitive requirements may reflect a generalized capacity sharing deficit for resolving multiple sensory signals. We suggest a ''cost'' in maintaining a compensatory state in which some baseline level of cognitive resources are required. From a neurophysiological perspective, compensation refers to a rebalancing of the neural activity in the vestibular nuclei through changes in the cerebellum, reticular formation, and other areas in the brain (for review, see Curthoys & Halmagyi, 1996). Functionally, compensation includes a resolution of symptoms of dizziness and disequilibrium resulting in a return to normal activities of daily living. From a clinical perspective, compensation also includes a reduction in signs of a vestibular imbalance such as spontaneous nystagmus and gait deviation, and a reduction in laboratory abnormalities such as positional nystagmus and directional preponderance. Also, clinical experience has found that symptoms can return under certain conditions, such as mental stress, anxiety, or physical illness (Herdman & Whitney, 2000; Shepard & Telian, 1995). Our results, especially the increased interference seen in patients during vestibular stimulation, suggest that the interaction of cognitive resources with vestibular ocular function may be one mechanism underlying these clinical observations of ''decompensation.''

Recent PET studies have shown that cognitive requirements during VOR fixation are a result, in part, of an inhibition among multiple sensory inputs. Deutschlander et al. (2002) found that vestibular stimulation can inhibit cortical activation induced by visual stimulation. Further, it is possible that vestibular and/or visual stimulation lead to interference with sensory processing during the auditory RT task, as inhibitory sensory–sensory interactions have been suggested by these studies. (Deutschlander, et al., 2002; Brandt, Bartenstein, Janek, & Dieterick, 1998) However, as we find interference between the two tasks during both vestibular stimulation in the dark and visual–vestibular interaction, our study design is limited in determining whether vestibular, visual, or both sensory inputs are interfering with the auditory task.

Auditory interference not specific to the dual-task experiment may also play some role in the particularly marked interference seen in the patient population during this study, as well as our previous dual-task study during postural control (Redfern, Talkowski, et al., 2004). As the patients in this study have undergone vestibular nerve resection, all patients are unilaterally deaf in their lesioned ear. Thus, as the control population is processing a binaural stimulus, the patients are processing only a unilateral auditory stimulus. This difference between populations may have led to a change in cognitive processing nonspecific to the visual or vestibular stimuli this experiment was designed to investigate. However, based on a prior study of control subjects who received a unilateral auditory stimulus, wherein we found no evidence for decreased performance (see Redfern, Talkowski, et al., 2004 for details), we do not believe that auditory deficits can fully account for the decreases in information processing performance seen in the present studies. Furthermore, in a previous study of patients with unilateral peripheral vestibular loss that included an inhibitory RT task in which the primary stimulus was *visual* (Redfern, Talkowski, et al., 2004), we found significant decreases in baseline performance in the patient group. Thus, we surmise that the deficits seen in the patient population during tasks with a requisite decision component are more reflective of a generalized deficit at later stages of information processing, such as sensory integration, and are not directly attributable to baseline auditory deficits.

A limitation in this and similar studies is the statistical power resulting from the relatively small number of patients studied, especially for the intergroup multiple comparisons. We necessarily restricted our available patient base by using stringent inclusionary criteria of surgically confirmed unilateral peripheral vestibular loss and complete functional compensation (see Methods for details). Although the within-group analyses have the benefit of repeated measures to increase statistical power, probes of between-group analyses have significantly reduced power due to the population sizes. Thus, we have been conservative in our interpretation of the intergroup results and our conclusions have been made in light of other published studies.

In summary, the results of this study suggest that the VOR interacts with cortical resources and is thus not automatic. We also have provided evidence for cognitive resource requirements during VOR fixation, but find that these requirements are not analogous to those involved in ocular pursuit, suggesting different mechanisms of cortical interactions for pursuit and VOR fixation. The findings suggest a link between higher cognitive centers and "reflexive" eye movements that is continually engaged. We also have replicated findings of generalized decreases in information processing task performance during tasks with a requisite decision component in patients with unilateral vestibular dysfunction. We find this effect to be enhanced by, but not strictly dependent on, a vestibular or visual–vestibular challenge and suggest it is representative of an ongoing increased cognitive requirement to maintain compensation for a unilateral vestibular insult. Further research is necessary to probe the clinical significance of these results.

METHODS

Subjects

Sixteen patients with unilateral peripheral vestibular loss (mean age = 50.6 ± 11.3 years; 9 women, 7 men) and 16 healthy age (±24 months) and sex-matched controls participated in this study. All patients had previously undergone a surgical procedure that resulted in a unilateral absence of vestibular function. Of the 16 patients, 14 underwent removal of an acoustic neuroma (vestibular schwannoma), and 2 underwent vestibular nerve sections to treat chronic Ménière's disease (endolymphatic hydrops). Further inclusionary criteria were established to help ensure that each of the patients was functionally compensated for the vestibular lesion, including: no current complaints of dizziness or imbalance, normal neurological exam by a neurologist, within normal limits on sensory organization tests 1–4 during computerized dynamic posturography (Nashner, 1993), and no history of head trauma. All patients were also required to have a pure tone average and speech reception threshold in their functional ear of 20 dB or less on audiological exam.

Subsequent to inclusion in the study, vestibular function was assessed in all subjects through a battery of vestibular laboratory tests, including binaural bithermal caloric irrigation, videonystagmographic recording of positional nystagmus, saccades, pursuit, optokinetic nystagmus, rotational testing at 0.02 and 0.05 Hz, 50°/sec peak velocity, and sensory organization testing using computerized dynamic posturography (see Furman & Cass, 1996). All patients also underwent ice water caloric irrigation of the surgical ear to confirm unilateral absence of vestibular function. Healthy, age-matched controls had no history of neurological impairment and clinically normal findings on vestibular testing as described above. To further ensure that the patients were clinically compensated from their vestibular lesion, functional balance tests were performed on all patients by a qualified vestibular therapist, including Functional Reach (Duncan, Studenski, Chandler, & Prescott, 1992; Duncan, Weiner, Chandler, & Studenski, 1990), Dynamic Gait Index (Shumway-Cook & Woollacott, 1995), and the Timed "Up-and-Go" (Shumway-Cook, Brauer, & Woollacott, 2000; Podsiadlo & Richardson, 1991). Finally, all subjects were also exposed to the OVAR to control for novelty of the stimulus and assure tolerance of the rotation prior to inclusion in the study. Subjects unable to tolerate the rotation stimulus were not included in the study. Generally, all subjects were able to tolerate the stimulus, and we found no differences in tolerance levels between patients and age-matched controls.

Instrumentation

A rotational chair capable of delivering an OVAR developed in our laboratory (Furman, Schor, & Schumann, 1992) was used in this experiment. The device consists of an 80 ft lb turntable attached to a chair in which the subject is restrained. Subjects are secured to the chair by over-the-shoulder and lap belts designed for automobile racing. The turntable, chair, and the enclosure that surrounded the subject are all placed on a platform that is hinged to a supporting structure. A hydraulic linear actuator is affixed beneath the platform and can smoothly tilt the entire apparatus (and thus, the axis of rotation) of the turntable off-vertical at a rate of 1.5°/sec to a maximum tilt of 30°. An inclinometer attached to the platform allows accurate control of the tilt angle.

The experimental apparatus also included hand-held microswitches for the RT tasks. Auditory stimuli were presented through a set of insert earphones at 560 or 980 Hz for 1 sec. Visual stimuli were presented with a 2-mm laser target 1 m in front of the subject. This system was previously used successfully to measure RTs during vestibular stimulation in elderly subjects (Furman, Muller, et al., 2003b).

Experimental Design and Protocol

Information Processing Tasks

The information processing tasks were three auditory RT tasks: simple RT, disjunctive (i.e., go/no-go) RT, and choice RT. Subjects were seated in the rotational chair and asked to hold a button joystick in the dominant hand for all tasks. A second button was held in the nondominant hand for the choice RT task. Subjects were presented with one of two tones, a low-frequency tone (560 Hz), or a high-frequency tone (980 Hz) at an intensity of 80 dB SPL. The tone frequencies were chosen based upon tabled values of center of frequencies critical bands (Zwicker & Flottrop, 1957). For each of the information processing tasks, a target tone (i.e., the low- or high-frequency tone) was randomly assigned to each patient and their age-matched control.

For the task protocols, subjects were presented with a tone stimulus and asked to respond as quickly and accurately as possible to the appropriate stimulus for the information processing task being conducted. For the simple RT and disjunctive RT tasks, subjects were instructed to respond to the target tone with their dominant hand. For the choice RT task, subjects were asked to respond to the target tone with their dominant hand and to the nontarget tone with their nondominant hand. The target and nontarget tones were each randomly presented in a ratio of 1:1. For the disjunctive RT task, subjects were instructed to respond to the target tone with their dominant hand as quickly as possible and not to respond to the nontarget tone. For the disjunctive RT task, nontarget tones were randomly presented in 37.5% of the trials.

Visual, Vestibular, and Visual–Vestibular Stimuli

Subjects were presented with seven different combinations of visual–vestibular stimuli in this experiment (Table 1). In the *vision-only* conditions, subjects were seated in the stationary rotational chair with three different forms of visual stimuli: darkness (Still/Dark), eyes fixated on a laser target (Still/Fixation), and horizontal pursuit of a laser target moving sinusoidally (0.2 Hz, ±20° from center) (Still/Pursuit). The target consisted of a discrete 2-mm laser point projected onto a screen 1 m in front of the subject (0.5 mW, 0.5° arc). The *vestibular-only* conditions consisted of two types of rotational stimuli in the dark, one a semicircular canal stimulus and the other an otolith stimulus. The semicircular canal stimulus was sinusoidal EVAR at 0.05 Hz and a peak velocity of 50°/sec (EVAR/Dark). The otolith stimulus was provided through a constant velocity (60°/sec) OVAR at a tilt angle of 30°. During the OVAR conditions, subjects were rotated using a rotate-then-tilt protocol (Furman, Schor, et al., 1992). OVAR was provided in both the clockwise (CW) and counterclockwise (CCW) directions (OVAR/Dark/CW, OVAR/Dark/CCW). This design was utilized to assure that patients were rotated in both directions with respect to their lesioned ear (i.e., ipsilesional and contralesional). A visual–vestibular interaction stimulus included sinusoidal EVAR at 0.05 Hz, 50°/sec peak velocity with a head-fixed visual target (EVAR/Fixation). This visual target was the same as the laser dot described above except that it moved with the chair. Thus, all subjects underwent these seven visual–vestibular conditions: (1) Still/Dark, (2) Still/Fixation, (3) Still/Pursuit, (4) EVAR/Dark, (5) EVAR/Fixation, (6) OVAR/Dark/CW, (7) OVAR/Dark/CCW.

Protocol

All subjects participated in one practice session and three test sessions were performed on different days. During the practice session, subjects were familiarized with the equipment and performed each of the three information processing tasks. An RT "trial" was defined as the presentation of the tone and a subsequent response by the subject. During the practice session, each information processing task was performed until RTs stabilized. Typically, simple RT stabilized within 96 trials, whereas the disjunctive RT and choice RT tasks required about 160 trials to stabilize. Feedback was provided on RTs and error rates during the practice trials. Subjects were always instructed to push the button as quickly as possible while also responding as accurately as possible. Instructions were repeated at the beginning of each test session to minimize instruction-dependent influences on performance, which have been shown to be potentially significant in dual-task studies (Levy & Pashler, 2001). All subjects were able to consistently perform the tasks with error rates less than 5%.

Each of the three information processing tasks was performed during a different test day. Test days were generally separated by no less than 48 hr and no more than 7 days. The RT task to be performed was crossed with each of the seven visual–vestibular stimuli described above. The seven visual–vestibular conditions were randomized into one ''block'' of test conditions, and two randomized blocks were performed during each test day. Thus, a total of 21 different information processing task + visual–vestibular condition combinations were collected twice for each patient and their age-matched control over the duration of the study. During each information processing task + visual–vestibular condition combination in each block, 32 trials were presented to the subject. For the EVAR conditions, trials began approximately ½ cycle, or 10 sec, after initiation of rotation. During OVAR conditions, trials began after the subject was tilted to 30° off-vertical. To control for predictability of stimulus onset, trials were presented randomly every 1.5 to 4 sec, with a mean interval between trials of 2.75 sec. Thus, each visual–vestibular condition + information processing task combination lasted approximately 90 sec. For all visual–vestibular condition + simple RT combinations, two ''catch trials'' were given in which at the expected time of a trial no tone was presented. These catch trials were included to increase alertness and decrease anticipation effects.

Data Analysis

Reaction times were recorded by a computer with a resolution of 1 msec. The median response time for each subject during each visual–vestibular condition + information processing task combination was calculated and used as an estimate for each subject's RTs for that combination. The RTs were then logarithmically transformed prior to statistical analysis to normalize the variance. Post hoc comparisons using specific contrasts were made for significant multiple-level variables. The analyses of the RTs were performed using repeated-measures analysis of variance with subjects nested within group. A significance level of $\alpha = .05$ was used throughout the analysis. Subsequent analyses were made on RTs that were normalized by subtracting the mean Still/Dark RT for the appropriate information processing task from the data for each subject. This procedure was used to determine the impact of vestibular and ocular motor processing on information processing task performance independent of baseline performance.

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