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The influence of cognitive tasks on vestibular-induced eye movements in young and older adults

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Abstract. The purpose of this study was to further investigate the mechanism of the influence of concurrent cognitive tasks on eye movements induced by earth-vertical axis rotation (EVAR) in young and older participants.

Ten young (ages 21–34), ten young-old (ages 65–74) and nine older participants (ages 75–84) each performed five different cognitive tasks during sinusoidal EVAR in darkness at 0.02 Hz for three cycles, 0.05 Hz for four cycles, and 0.1 Hz for five cycles, all at a peak velocity of 50 degrees per second. The five tasks differed from one another in terms of their inherent sensory and motor components and were designed to provide insight into the effect of cognitive processing on VOR dynamics. Tasks included auditory frequency and lateralization disjunctive reaction time (DRT) tasks, silent and audible backward counting, and a question-response clinical standard task. For the DRT trials, tones were presented to the participant through earphones. Participants were instructed to respond as accurately and as quickly as possible. Eye movements were recorded with electro-oculography and calibrations were performed before and after every five rotations in all subjects.

Participants had an increase in VOR phase lead while performing DRT tasks as compared to the clinical standard and counting tasks. The effect was most noticeable at the 0.02 Hz frequency and was present in all age groups. In addition, we observed a decrease in VOR gain while subjects performed auditory DRT tasks during EVAR at 0.02 Hz, 0.05 Hz and 0.1 Hz as compared to the clinical standard and counting tasks. These results suggest cognitive task-dependent interference between central auditory processing and vestibular processing primarily at the sensory rather than at the motor level.

1. Introduction

There is growing interest in the relationship between balance disorders and cognition [13]. Patients with balance disorders often complain of difficulty concentrating, performing arithmetic, and other basic cognitive skills. During clinical vestibular laboratory evaluation as well, there has been anecdotal reporting of increased difficulty performing simple tasks like counting backward. An association between cognitive processing and balance has been documented experimentally in both normal adults and in patients with vestibular disorders [30,37,43].

Dual-task paradigms have been used to study interference between cognitive processing, particularly attention, and the vestibulo-ocular reflex (VOR) [10, 42] and postural stability [6,27,30]. These studies have been helpful in identifying shared cognitive resources under a variety of conditions. Dual-task experiments have demonstrated interference between maintaining balance and performing tasks such as mental arithmetic [6], visuospatial tasks [1], reaction-time tasks [10,30], word recall [20] and verbal response

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tasks [9]. The interference found in performing these tasks may be the result of a common neural pathway or of sharing a total capacity of attentional resources.

Whereas many dual-task studies evaluate vestibulospinal performance, relatively few examine VOR dynamics. Like interference between the vestibulospinal system and cognitive processing, similar interference has been noted between visual-vestibulo-ocular system activation and cognitive tasks [10,42]. In particular, reaction times were increased, and eye movements were altered when performing reaction time tasks during rotation [10,37]. Increased phase lead was found to be a sensitive indicator of VOR dynamics and reflects a change in the velocity storage system [28,32]. By impacting phase, attentional processes appear to influence velocity storage in the VOR [10]. The components of the vestibular response may therefore provide insight regarding a mechanism of interference.

Aging seems to play an important role in the interference between attention and vestibular processing. Confusion and distraction often influence loss of balance and falling in the elderly [14]. Studies of interference between attention and vestibulospinal control indicate a greater effect with increased age [6,22,30,35,36,38,39]. The VOR also changes with age, showing decreased gain and increased phase lead [4,10,26]. This study assessed whether aging is associated with a relative increase in interference between specific cognitive tasks and the VOR.

Prior studies have not compared the effects of different alerting tasks on eye movements during VOR activation. This study examines cognitive tasks that involve various motor and sensory components to assess an approximate location of dual-task interference. Tasks included two disjunctive reaction time (DRT) tasks, a clinical standard task, and silent and audible backward counting. Both DRT tasks involve auditory processing and a button-push response, while being distinguished by frequency or spatial discrimination. The clinical standard task is a commonly-used question and answer alerting task involving hearing a letter, finding a word, and providing a verbal response. Both counting tasks involve mental arithmetic while being distinguished by an audible counting task requiring a verbal response. Based on results from Furman et al. [10] indicating prolonged phase with auditory processing tasks, we hypothesized that there would be greater interference with VOR dynamics for auditory reaction time tasks that are more sensory based than motor. Additionally, we hypothesized that VOR gain would not be affected differently by different cognitive tasks.

2. Methods and materials

2.1. Subjects

This study was approved by the University of Pittsburgh Institutional Review Board. Subjects included 10 young subjects (5 men) with mean (SD) age 24.7 (2.7) years, 10 young-old subjects (5 men) of age 69.7 (3.0) years and 9 old-old subjects (4 men) of age 79.7 (3.0) years.

Subjects were excluded if they had a history of neurological or otological disease, binocular visual acuity with corrective lenses worse than 20/40 in both eyes, abnormal audiometric function based on a 15 dB asymmetry at any test frequency or thresholds below the bottom 10% of age-adjusted values, significant abnormalities on neurological examination, abnormal ocular motor testing, abnormal vestibular function based on abnormal caloric responses or a significant directional preponderance on EVAR, or performance worse than $1^1/_2$ SD below age-adjusted means on 2 or more categories of the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS).

Subjects qualified for participation in this study by successful completion of a prior study involving rotational testing. 60 subjects participated in the source study and were recruited from a registry of older adults and from the Pittsburgh community via advertisements. Sixteen older and 3 younger subjects were excluded from enrolling in the source study due to failure of audiometric testing (8), neuropsychiatric testing (4), use of excluded medications (4), poor RT assessment (2), and directional preponderance on rotation testing (1). Of the 60 subjects who successfully completed the source study, 15 subjects who developed nausea during the source study did not participate in this second study. Of the remaining 45 subjects, 30 were recruited for this study. Subjects received payment for participation in this study.

2.2. Rotational testing

All subjects underwent electrooculographic (EOG) recordings of eye movement during rotational testing using sinusoidal earth vertical axis rotation (EVAR) at 0.02 Hz for three cycles, 0.05 Hz for four cycles, and 0.1Hz for five cycles, all with a maximum velocity of 50 degrees/second. The number of cycles was chosen to allow reliable assessment of VOR dynamics while keeping total test time short. Subjects were rotated in complete darkness throughout all trials. Gain and phase of the VOR were estimated from eye movements recorded with EOG. EOG calibrations were taken every 5 trials to avoid the effects of fluctuations in the corneoretinal dipole potential. Minimal changes were noted in EOG calibrations during testing.

2.3. Cognitive tasks

During rotation at each frequency of sinusoidal EVAR, subjects were asked to perform each of five different cognitive tasks. Tasks included auditory frequency and lateralization Disjunctive Reaction Time (DRT) tasks, silent and audible backward counting, and a question-response clinical standard task. Tasks were selected to differentiate sensory, central processing and motor components in order to understand the effects of different cognitive processing components on VOR dynamics.

For the DRT tasks, tones were presented to the participant through insert earphones (details below). Participants were instructed to respond as accurately and as quickly as possible by pressing a hand-held button. The tones were presented at random intervals between 2.5 and 4.0 seconds and were present for 1 second at an intensity of 80 dB SPL. The auditory frequency DRT task presented a high (980 Hz) or low (560 Hz) frequency tone to both ears. No masking was used, and the interaural attenuation of the insert earphones is approximately a 40 dB ambient noise reduction at the presented tonal frequencies [34].

Participants held a button in both their dominant and non-dominant hands. For the target frequency, randomly the high or low tone for each subject, the participant was instructed to press the button in their dominant hand and for the alternative frequency the participant was not to press a button. In the lateralization task, if the tone was presented to the ear on the side of the participant's dominant hand, the participant was instructed to press the button with their dominant hand. If the tone was presented to the ear on the side of the participant's non-dominant hand, the participant was not to press the button. For instance, if a right-handed participant was performing the lateralization task, a tone played in their right ear would be followed by their pressing a button in their right hand, whereas a tone played in their left ear would not evoke a response.

For the two counting tasks with no sensory component, participants were asked to count backward from 1000 by 3 either silently (no sensory or obvious motor component) or aloud (no sensory component). If the counting was silent, participants were instructed to provide the final number at the trial's end.

The clinical standard task was similar to a verbal fluency task in which subjects listened to prerecorded questions through earphones and provided a verbal response if possible. This task was intended to represent current clinical practice of asking questions to keep participants alert. Participants listened to a randomly-generated subset of 24 letters presented at 2 second intervals. Depending on the trial, participants were instructed to provide a location, an animal or a type of food that begins with the spoken letter. Audio from these trials was monitored, but accuracy was not assessed.

2.4. Protocol

The study consisted of 1 practice day and 1 test day. During the practice day, subjects were familiarized with the testing equipment and each of the cognitive tasks. Each of the reaction-time tests was practiced for at least 3 EVAR trials of 30 reaction times. Results from the practice day were assessed and additional trials were performed until the participant understood the task.

On the test day, participants performed all five cognitive tasks at 0.1 Hz, 0.05 Hz and 0.02 Hz EVAR. The order of task and frequency were randomized. During each of the two auditory DRT task and rotational frequency combination, participants were presented with 32 reaction-time trials. During each trial, cognitive tasks were begun shortly after beginning EVAR.

2.5. Equipment

A rotational chair capable of delivering EVAR was used for this study. Hand-held microswitches were used for reaction time tasks. For auditory DRT tasks, auditory stimuli were presented through insert earphones (Model ER2, Etymotic Research, Elk Grove Village, IL, USA).

2.6. Data analysis

The primary dependent variables for each trial were derived from the eye movement data. The level of performance on the specific tasks was recorded, but not analyzed statistically. VOR gain and phase were computed using standard techniques. EVAR cycles during which no nystagmus was observed or during which the cycle was predominated by nystagmus dysrhythmia were excluded from further analysis [10]. Only

Table 1
Phase lead, in degrees, by frequency, age group, and task during earth-vertical axis rotation

Frequency	Group	Auditory Frequency DRT	Lateralization DRT	Clinical Standard	Audible Counting	Silent Counting	Average
0.02 Hz	Young	27.0 (4.6)	26.9 (7.2)	22.2 (4.8)	23.3 (5.9)	23.8 (7.5)	$24.6^{\pm}$ (6.0)
	Young-old	27.5 (10.6)	32.5 (12.2)	24.2 (11.5)	27.3 (12.9)	26.3 (13.8)	27.4 (12.0)
	Old-old	35.1 (6.5)	36.9 (7.5)	27.4 (8.1)	28.0 (9.6)	31.0 (7.7)	$31.4^{\pm}$ (8.5)
	Average	29.5 (8.3)*	31.6 (9.9)*	24.5 (8.6)	26.2 (9.8)	27.0 (10.4)	27.6 (9.6)
0.05 Hz	Young	9.0 (5.0)	9.4 (3.1)	10.0 (3.8)	8.6 (5.0)	9.5 (3.0)	$9.3^{\dagger}$(3.9)
	Young-old	13.3 (6.9)	10.9 (8.4)	12.0 (5.6)	10.2 (6.8)	12.1 (6.9)	$11.7^{\dagger}$ (6.8)
	Old-old	16.1 (4.1)	17.1 (4.7)	15.7 (4.5)	16.1 (6.7)	16.9 (7.8)	$16.4^{\dagger}$(5.6)
	Average	12.6 (6.2)	12.1 (6.6)	12.4 (5.1)	11.5 (6.9)	12.7 (7.0)	12.3 (6.3)
0.10 Hz	Young	1.4 (4.6)	4.3 (4.4)	3.3 (2.8)	3.4 (3.5)	3.8 (2.6)	$3.2^{\ddagger}$(3.6)
	Young-old	4.5 (6.5)	2.8 (5.9)	5.3 (5.3)	4.9 (7.9)	4.9 (6.9)	$4.5^{\ddagger}$(6.3)
	Old-old	7.1 (2.1)	6.5 (3.1)	9.6 (4.9)	8.5 (10.3)	9.7 (8.5)	$8.4^{\ddagger}$(6.6)
	Average	4.2 (5.3)	4.3 (4.9)	6.0 (5.0)	5.5 (7.7)	6.0 (6.8)	5.2 (6.1)

Values in parentheses are standard deviations. * indicates significant difference from the clinical standard task in post-hoc tests.
$^{\pm,\ddagger}$ and † indicate significant difference at $p < 0.05$.

Table 2
Gain by frequency, age group, and task during earth-vertical axis rotation

Frequency	Group	Auditory Frequency DRT	Lateralization DRT	Clinical Standard	Audible Counting	Silent Counting	Average
0.02 Hz	Young	0.43 (0.13)	0.39 (0.11)	0.54 (0.12)	0.54 (0.14)	0.47 (0.16)	$0.47^{\pm}$ (0.13)
	Young-old	0.28 (0.13)	0.33 (0.13)	0.49 (0.20)	0.45 (0.17)	0.39 (0.13)	0.39 (0.16)
	Old-old	0.28 (0.07)	0.24 (0.08)	0.43 (0.15)	0.38 (0.11)	0.33 (0.11)	$0.34^{\pm}$ (0.12)
	Average	0.33 (0.13)*	0.33 (0.12)*	0.49 (0.16)	0.46 (0.15)	0.40 (0.14)*	0.40 (0.16)
0.05 Hz	Young	0.54 (0.13)	0.53 (0.15)	0.72 (0.15)	0.62 (0.12)	0.57 (0.14)	$0.59^{\dagger}$ (0.14)
	Young-old	0.37 (0.09)	0.34 (0.10)	0.51 (0.19)	0.49 (0.16)	0.48 (0.16)	0.44 (0.16)
	Old-old	0.30 (0.15)	0.34 (0.11)	0.52 (0.11)	0.51 (0.12)	0.41 (0.12)	$0.43^{\dagger}$ (0.15)
	Average	0.41 (0.16)*	0.41 (0.15)*	0.58 (0.17)	0.54 (0.14)	0.49 (0.15)*	0.49 (0.17)
0.10 Hz	Young	0.47 (0.15)	0.47 (0.14)	0.70 (0.08)	0.64 (0.11)	0.62 (0.12)	$0.58^{\ddagger}$ (0.12)
	Young-old	0.38 (0.16)	0.36 (0.11)	0.53 (0.19)	0.43 (0.13)	0.44 (0.21)	0.43 (0.17)
	Old-old	0.37 (0.10)	0.30 (0.11)	0.58 (0.10)	0.51 (0.17)	0.46 (0.14)	$0.45^{\ddagger}$ (0.15)
	Average	0.41 (0.15)*	0.38 (0.14)*	0.60 (0.15)	0.53 (0.16)	0.50 (0.18)*	0.49 (0.17)

Values in parentheses are standard deviations. * indicates significant difference from the clinical standard task in post-hoc tests.
$^{\pm}$, †, ‡indicate significant difference at $p < 0.05$.

normal-appearing nystagmus was used for computing VOR gain and phase. We did not attempt to compute phase for trials with VOR gain of less than 0.2. Means and SD were calculated for VOR phase and gain for each frequency, age group, and cognitive task. In addition, using the fminsearch function in Matlab (The Mathworks$^{\mathrm{TM}}$), gain and phase data were fit with a simple first-order linear systems model of the form $kappa \bullet \frac{tau \bullet s}{tau \bullet s+1}$ where kappa is VOR sensitivity, tau is the VOR time constant, and s is the Laplace operator. The rationale behind estimating sensitivity and time constant is that the gain and phase data at all of the frequencies tested can be collapsed into a single measure of VOR magnitude and a single measure of VOR dynamics.

Statistical analyses used two-way ANOVA with repeated-measures using a significance level of 0.05. Cognitive task was a within-subject factor and age group was a between-subject factor. Eight separate ANOVA were performed; one ANOVA was performed for tau, one for kappa and one for each of phase and gain at each of the three frequencies: 0.02 Hz, 0.05 Hz, and 0.1 Hz.

3. Results

Tables 1 and 2 provide an overview of the results for phase and gain for each of the five cognitive tasks during EVAR at the three frequencies tested in each of three age groups. Accuracy during reaction time tasks was greater than 90% for all groups during all conditions.

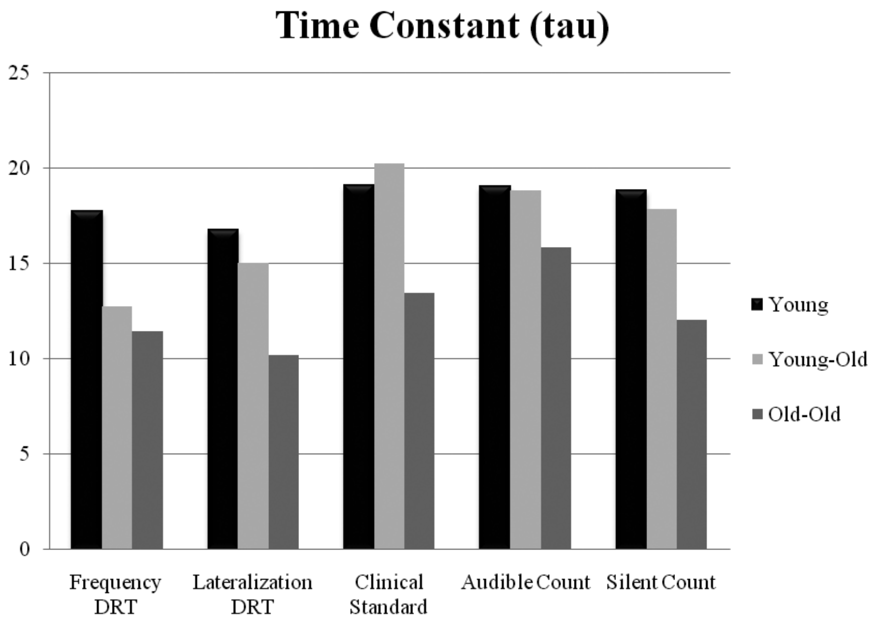

Fig. 1. VOR time constant based on a first order model.

3.1. *Phase*

To assess the effect of task on phase lead, we used age group as a between-subject variable and task as a within-subject variable. This analysis showed an overall task effect at 0.02 Hz ($p < 0.001$), and an age group effect at 0.02 Hz ($p < 0.001$), 0.05 Hz ($p < 0.001$) and 0.1 Hz ($p < 0.001$). For the task effect on phase at 0.02 Hz, post-hoc analysis was performed between the DRT and counting tasks and the clinical standard task and between the DRT tasks and the counting tasks. This analysis indicated that both frequency and lateralization auditory DRT tasks had a significantly prolonged phase as compared to the clinical standard and counting tasks ($p < 0.001$). For the age group effect on phase at 0.02 Hz, 0.05 Hz and 0.1 Hz, post-hoc analysis indicated that phase was significantly increased for the old-old group as compared to the young group ($p < 0.01$). At 0.05 Hz and 0.1 Hz phase was also significantly increased in the old-old group as compared to the young-old group ($p < 0.01$). There were no interaction effects between age group and cognitive task for any frequency, suggesting that the subject's age did not influence the interference between cognitive task and VOR phase.

3.2. *Gain*

In order to assess the effect of task on gain, we similarly used age group as a between-subject variable and task as a within-subject variable. This analysis showed an overall task effect and age group effect at all tested frequencies ($p < 0.001$). Post-hoc analysis was also performed between the DRT and counting tasks and the clinical standard task and between the DRT tasks and the counting tasks. This analysis indicated that at all frequencies, gain was decreased significantly for frequency and lateralization auditory DRT tasks as compared to the other three tasks ($p < 0.01$). There was no difference in gain between the frequency and lateralization auditory DRT tasks at any rotational frequency. The silent counting task had significantly decreased gain as compared to the clinical standard task and increased gain as compared to the DRT tasks at all frequencies ($p < 0.01$). VOR gain during the audible counting task did not differ from the clinical standard task at 0.02 Hz and 0.05 Hz, but was significantly decreased from the clinical standard task at 0.1 Hz ($p < 0.01$). For the age group effect on gain at 0.02 Hz, 0.05 Hz and 0.1 Hz, post-hoc analysis indicated that gain was significantly decreased for the old-old group as compared to the young group ($p < 0.01$). As for phase, there were no significant interactions between age group and cognitive task for VOR gain at any frequency.

3.3. *First-order VOR model analysis*

To better characterize our results, we collapsed phase lead and gain across frequency into an estimate of VOR

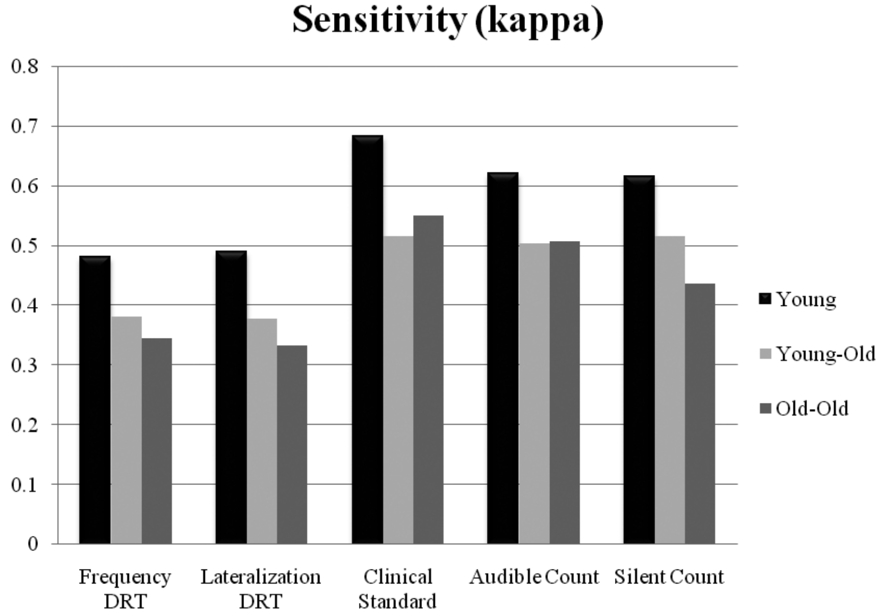

Fig. 2. VOR sensitivity based on a first order model.

time constant and sensitivity. For time constant (Fig. 1), ANOVA indicated an overall task effect ($p = 0.001$) and age group effect ($p < 0.001$). Post-hoc analysis for task effect revealed shorter time constant for both DRT tasks as compared to the clinical standard task ($p = 0.035$) and the audible count task ($p = 0.01$). Time constant was shorter for the old-old group as compared to the young-old group and the young group ($p < 0.01$). There was no difference in time constant between the young and young-old group.

For sensitivity (Fig. 2), ANOVA also indicated an overall task effect ($p < 0.001$) and age group effect ($p < 0.001$), with both DRT tasks having lower sensitivity as compared to the clinical standard and counting tasks ($p < 0.001$). Sensitivity was not significantly different between the frequency and lateralization auditory DRT tasks. The silent counting task had a lower sensitivity as compared to the clinical standard task and a higher sensitivity as compared to the DRT tasks ($p < 0.01$). The audible counting task also had a lower sensitivity as compared to the clinical standard task, but a higher sensitivity as compared to the DRT and silent counting tasks ($p < 0.01$). In addition, sensitivity was significantly decreased for both older groups as compared to the young group ($p < 0.01$); however, there was no significant difference in sensitivity between the older groups. There were no interactions between age group and cognitive task for either time constant or sensitivity.

4. Discussion

This study extends an observation by Furman et al. [10] of increased phase lead at low frequency EVAR during a concurrent auditory reaction time task. The increased phase lead at low frequencies corresponds to a shorter VOR time constant, which is generally considered a measure of the efficiency of the velocity storage integrator [7,28,29]. Therefore, the interference between cognitive tasks and the VOR, manifesting as increased phase lead at low frequencies, may be attributed to a less efficient velocity storage integrator during task performance.

In addition to altered low frequency phase and time constant, this study has shown that VOR gain during EVAR is reduced during auditory DRT tasks as compared to counting tasks and the current clinical standard. Previous research into the determinants of gain has identified the importance of alertness [21] and mental set [19] during rotation in darkness. Rotational gain approaches 1.0 when subjects focus on an earth-fixed point, whereas gain approaches 0.1 when subjects imagine a stimulus that moves with the head [19]. Each of the five different tasks used in this study are considered to be equally alerting. In fact, the clinical standard task was selected because of its known capability for keeping patients alert during clinical vestibular testing. Thus, our finding that different cognitive tasks influence VOR gain differently is attributable to some inherent attributes of the tasks rather than simply their ability to alert the subjects during rotational testing.

At low frequency rotation in this study, VOR gain decreased and phase lead increased while performing a concurrent auditory disjunctive reaction time task. This pattern of increased phase lead, corresponding to a decreased time constant, and decreased gain has been documented previously in humans with peripheral vestibular disease [3,15], during VOR adaptation [16–18] and during aging [2]. Other studies have noted that patients with migraine have altered VOR gain, but no changes in time constant as compared to controls [11]. In patients with anxiety disorders, however, gain and time constant both appear to increase [12,44]. Using a short-term adaptation paradigm to adjust VOR gain and phase, Kramer et al. [18] noted that when adjusting for either VOR gain or phase, the other variable changed, but the relationship was nonlinear. Mathematical models of the VOR, such as the one described by Kramer et al., would predict that a decrease in time constant and a decrease in gain could both be explained by impaired velocity storage. However, since gain and time constant may be differentially affected, the relationship between VOR phase and gain remains uncertain. Nevertheless, the findings in this study that phase lead increased, corresponding to a shorter time constant, and gain decreased during the performance of an auditory DRT task suggest that velocity storage may be impaired during these concurrent cognitive tasks because of the equally alerting nature of the tasks.

The intent of studying dual-task interactions in this experiment was to determine the approximate location of interference. Some theories of dual-task interactions include capacity theories, in which a person is suggested to have a limited total capacity to perform tasks. If this capacity is exceeded, task performance in one or both tasks is sacrificed [40,41]. Since there is no standard to assess the difficulty of the various tasks used in this study, it cannot be definitely stated that these results support or refute the capacity hypothesis of dual-task interference. However, the results indicate greater interference for auditory DRT tasks than for a task in which participants are asked to respond to questions (a potentially more difficult task). Moreover, in this selective sample there were no effects of age on the interference between cognitive task and the VOR. We therefore suggest that the cognitive interference seen in this study can be attributed to inherent aspects of the task such as sensory stimulation or motor inhibition rather than to task difficulty.

The tasks used in this study were chosen for their sensory and motor components in order to approximate anatomic locations of interference. Each task involved a central processing component, but differed in its sensory and motor components. In addition, the different auditory DRT tasks were selected to determine if spatial localization interfered with VOR dynamics. These DRT tasks required the participant to sense an auditory stimulus, process the stimulus centrally, and provide a motor response. That there was consistently no difference between these tasks indicates that the effects seen on gain and phase were not related to the frequency or spatial localization of the auditory stimulus. Audible backward counting is primarily a motor task and silent backward counting includes neither a motor nor a sensory component. Although phase or time constant was not different from the clinical standard while performing counting tasks, gain while performing these tasks was decreased at all frequencies, but not to the extent of the DRT tasks.

Increasing evidence in recent decades has emphasized the behavioral state-dependent nature of the VOR and has focused primarily on motor commands rather than on sensory stimulation. Current studies of the state-dependence of the VOR have examined the influence of gaze shifts indicating VOR suppression by efference copy [8,33]. However, since VOR gain and phase are both significantly altered toward decreased gain and increased phase, it is more likely that the auditory DRT tasks are causing VOR degradation than gain suppression by efference copy. Alternatively, VOR suppression has also been documented via sensory input causing cerebellar inhibition of floccular target neurons in the vestibular nuclear complex [5]. VOR suppression seen in this study may similarly occur via cerebellar inhibition due to sensory context.

Both auditory DRT tasks involved motor commands, but were in part distinguished from the other tasks by their auditory sensory component. Furman et al. [10] suggested in a prior study that increased reaction time to an auditory stimulus under vestibular conditions and a corresponding prolonged phase could have been due to interference between auditory sensory input and vestibular stimulation. Redfern et al. [31] indicated in a postural control study similar prolongation of reaction time associated with auditory stimuli during balance perturbations. In this study, both DRT tasks affected VOR gain and phase similarly, indicating that spatial location of the auditory stimulus was not influential. The greater effect on VOR activation during auditory DRT tasks could be attributed to central sensory interference between auditory and vestibular processing, though precise localization of the interference seen in this study is unknown.

Finally, an additional explanation for greater suppression of the velocity storage mechanism of the VOR seen in the DRT tasks involves inhibition. The motor component of the auditory DRT tasks is disjunctive and therefore involves the participant inhibiting an incorrect motor response. Recent work on motor inhibition has indicated a relationship between inhibiting voluntary hand and eye movements [24]. The influence of an inhibitory task on other concurrent processes is known as interference control [23]. In this study, the cognitive requirements of inhibiting an incorrect motor response may be suppressing the velocity storage component of the VOR. A purely sensory task such as counting target tones may have distinguished between auditory processing and inhibition as the origin of interference. Future studies will assess the role of cognitive task inhibition in influencing the VOR.

An effect of aging was again seen in this study for both gain and phase. Prolonged phase in the older groups and decreased gain as compared to the younger group was evident at all frequencies. This increase in phase lead and decrease in gain may be due to age-related deterioration of the velocity storage integrator [25,26]. Despite this effect of age, however, there was neither an effect of age on the amount of interference nor on the type of task that interfered with the VOR. It therefore appears that the interference between cognitive task and vestibular function seen in this study is inherent to the task and independent of age. One of the limitations of this study is the relatively high-function of the elderly groups. Due to the requirements of the study, exclusion criteria limited the elderly sample to those with minimal visual and auditory impairments. Although there was no interaction seen with age and task interference with the VOR in this study, a similar study with a more representative sample of older adults may reveal such an interaction.

In summary, this study indicates interference between central auditory processing and vestibular processing that appears to be independent of age and primarily sensory rather than motor, though the role of motor inhibition should be considered in future studies.

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