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Suppression of the Vestibulo-Ocular Reflex Using Visual and Nonvisual Stimuli

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Abstract

Purpose: To determine to what extent attention directed toward visual, auditory, somesthetic, and imaginary sources would attenuate the vestibulo-ocular reflex (VOR).

Method: Two prospective studies included 16 (Investigation 1) and 5 (Investigation 2) healthy participants (mean age of 24 years in Investigation 1 and 37 years in Investigation 2). VOR gain was assessed with a commercially available rotary chair and was measured in dark both while the subject was tasked with mental alerting exercises and while not being tasked. VOR suppression was measured for the following conditions: (a) visual suppression, (b) auditory suppression, (c) somatosensory suppression, (d) imaginary visual target suppression, and (e) combined auditory and somatosensory suppression.

Results: Attention directed to visual source attenuated the VOR by approximately 85%. Attention directed toward auditory and somatosensory targets (both separately and combined) and attention directed toward an imaginary target suppressed the VOR between 28% and 44%. The extent of VOR suppression that occurred with attention directed toward various nonvisual stimuli was significantly less than the visual suppression of the VOR. The various nonvisual conditions were not statistically different from one another.

Conclusion: The data suggest that it is possible for typical adults to suppress the VOR in the absence of a visual target. That is, the VOR can be attenuated with attention directed toward chair-fixed visual, auditory, somatosensory, and imaginary targets.

Keywords

audiology; balance; physiology; vestibular rehabilitation

The ability to maintain balance, posture, and orientation makes it possible for us to perform automatic tasks, such as standing upright or walking, and more complex activities, such as sports. Inputs from vision, proprioceptive, and vestibular systems are integrated by the central nervous system, which initiates appropriate motor outputs that enable us to have stable balance.

The peripheral vestibular system routes electrical signals to the central vestibular system and from there to the ocular motor pathways to produce compensatory eye movements during movement of the head or head and body together. It is this vestibulo-ocular reflex (VOR) that stabilizes images of interest on the retina during movement of the head. However, in some instances, it is necessary to “suppress” the VOR. For example, when we are sitting in the grandstands, at the level of the net, watching a tennis match, we do not want our eyes to deviate in the direction opposite the movement of the head as we follow the ball back and forth. In this situation, central processes are recruited to suppress the VOR to permit volitional eye movements to keep an image of interest (e.g., the tennis ball in this case) centered on the fovea of the retina during movement of the head (Konrad, Girardi, & Helfert, 1999). The ability to suppress the VOR also is necessary in the presence of disease when one vestibular end organ is impaired. When this occurs, the tonic electrical asymmetry between the functioning and nonfunctioning end organs produces a spontaneous nystagmus that results in an illusory movement of the environment. In this situation, suppression of the VOR (i.e., by centers in the cerebellar midline) restores a tonic symmetry in the vestibular nuclei and a reduction or elimination of both the spontaneous nystagmus and the vertigo.

The parameter used to quantify VOR suppression is VOR gain. VOR gain is defined as the maximum slow-phase eye velocity (i.e., maxSPEV), divided by the velocity of the head. Under perfect conditions, the VOR produces conjugate eye movements that are equal and opposite the direction of the head movement (i.e., 180° out of phase), resulting in a gain value of 1.0.

VOR suppression is best assessed during rotational testing, which is a “natural” stimulus (i.e., a stimulus that produces excitation of one end organ and simultaneous inhibition of the other). The patient is instructed to stare at an illuminated target that travels with the chair as the chair is oscillated side to side. The results of several studies have shown that VOR suppression is largest in magnitude when it is assessed during rotary chair testing. Visual VOR suppression has been reported to vary between 75% and 90% for rotational testing (Brey, McPherson, & Lynch, 2008) compared with during caloric testing, where VOR suppression has been reported to reduce induced nystagmus by 40%–70% (Barber & Stockwell, 1980). An additional advantage of using rotational testing is that the VOR suppression can be quantified at multiple frequencies.

Although it is well known that connections between the vision, eye movement, and vestibular systems underlie both static and dynamic VOR suppression, a series of investigations conducted over the past 35 years have attempted to assess VOR suppression in the absence of vision using nonvisual targets, including “imagined” visual targets, visual afterimages, somatosensory targets, and auditory targets (Barr, Schultheis, & Robinson, 1976; Furst, Goldberg, & Jenkins, 1987; Jones, Berthoz, & Segal, 1984; Moller, White, & Odkvist, 1990). The results of these investigations suggest that attention directed toward nonvisual targets (e.g., auditory and/or somatosensory targets) may attenuate the VOR. None of these investigations have been replicated. Further, no one has offered an explanation for VOR attenuation where nonvisual targets were used for VOR suppression testing. Accordingly, the objectives of the current investigation were (a) to reassess to what extent attention directed to visual and nonvisual targets can suppress the VOR, (b) to determine

how comparable are the values we measure compared with those obtained from previous investigations, and (c) to determine what might be the possible origin of VOR suppression if VOR suppression occurs for nonvisual targets.

Investigation 1

Method

The initial investigation included 16 participants (4 men; mean age = 24 years; range = 21–30 years) with no history of otologic or neurological diseases or disorders. Hearing thresholds at 500, 1000, 2000, and 4000 Hz were obtained on all subjects to ensure normal hearing sensitivity during a screening process. Subjects were recruited from within the Division of Audiology of the Department of Hearing and Speech Sciences at Vanderbilt University. Each subject served as his or her own control. All testing was completed at the Balance and Disorders Center in the Division of Vestibular Sciences at the Vanderbilt Bill Wilkerson Center for Otolaryngology and Communication Sciences. The investigation was approved by the Institutional Review Board at Vanderbilt University (IRB00000477), and subjects provided full informed consent.

Subjects were seated in a commercially available, sinusoidal harmonic acceleration (SHA) chair (Micromedical Technologies System 2000). The chair was enclosed in a light-proof room. SHA testing was conducted at frequencies of 0.02 Hz, 0.08 Hz, and 0.32 Hz (i.e., maximum velocity of 50 degrees per second). Infrared video-oculographic recording techniques were used to record eye position. Only VOR gain will be reported in this investigation, as this is a VOR suppression study, and many times there was insufficient nystagmus to calculate VOR phase and symmetry. VOR gain was quantified as a percentage with a range from 0% to 100% (i.e., gain of 1.0 = 100%). To calculate the magnitude of VOR suppression, we recorded the maxSPEV for each frequency in darkness and then for the various conditions in this investigation. VOR suppression was calculated as $[1 - (\text{VOR gain in each of the suppression conditions} / \text{VOR gain in darkness})] * 100$. Communication between the examiner and subject was accomplished with a wireless intercom system.

Each subject completed five conditions at each frequency (i.e., 0.02 Hz, 0.08 Hz, and 0.32 Hz). All conditions were performed in the dark with the subject's eyes open. The conditions are described in Table 1. For Condition 1, subjects were oscillated in the dark while engaged in mental alerting exercises. Condition 2 was the same as Condition 1 without the mental tasking. The other three conditions were the VOR suppression conditions. During Condition 3, subjects were oscillated in the dark and while in motion asked to stare at a laser target that moved with the chair and was presented at center gaze (visual suppression). For Condition 4, an auditory stimulus was played from a sound source affixed to a vertical metal bar that had been mounted on the footplate of the rotary chair (auditory suppression). The sound source was presented at a comfortable loudness (i.e., 62 dBA) and at 0° azimuth. While the chair was moving, the subject was asked to listen and to stare in the dark at the location of the sound source. For Condition 5, the subject was instructed to grasp a vertical bar mounted on the footplate of the rotary chair (somatosensory suppression). Subjects were further requested to stare at the hand grasping the bar. Data were collected from a minimum of two cycles (i.e., complete chair oscillations) for 0.02 and 0.08 Hz and from a minimum of four

cycles for 0.32 Hz. Calibration was completed before each trial. Each condition (i.e., darkness with tasking, darkness without tasking, visual suppression, auditory suppression, somatosensory suppression) was replicated once at each frequency (i.e., 0.02, 0.08, and 0.32 Hz) in a randomized order (Latin square randomization). In all, there were 30 trials for each subject (i.e., 3 frequencies $\times$ 5 conditions $\times$ 2 runs).

Results

Results are shown in Table 2. VOR gain was greatest for Conditions 1 and 2 (darkness with and without tasking), with a three-frequency mean gain of 47.8 and 44.7, respectively. VOR gain was significantly smaller for all three suppression conditions. VOR gain was similar for Conditions 4 and 5 (auditory and somatosensory suppression), with a three-frequency mean gain of 33.1 and 32.6 for Conditions 4 and 5, respectively. VOR gain was smallest for Condition 3 (visual suppression), which resulted in a three-frequency mean gain of 6.4. In general, results suggested that VOR suppression occurred during all three suppression conditions but was greatest for the visual suppression condition.

The data were analyzed with a repeated measures analysis of variance (ANOVA), where VOR gain (i.e., range of 0–100) served as the dependent variable and the variables run (two levels), frequency (three levels), and condition (five levels) served as grouping variables. The results revealed that although VOR gain did not decrease significantly between Runs 1 and 2 ($p = .177$), there were significant main effects noted for the variables frequency, $F(2, 30) = 4.23$, $p = .015$; and condition, $F(4, 60) = 156.42$, $p < .001$.

Post hoc analysis (Bonferroni) showed that VOR suppression was poorer (i.e., the VOR gain was greater across conditions) for 0.02 Hz compared with 0.08 Hz ($p = .02$). Post hoc analysis (Bonferroni) also showed that VOR gains for Conditions 1 and 2 (i.e., controls with Condition 1 and without Condition 2 alerting exercises) were significantly larger ($p < .001$) when compared with VOR gain for Condition 3 (visual suppression, $p < .001$), Condition 4 (auditory suppression, $p = .001$), and Condition 5 (somatosensory suppression, $p < .001$). VOR gain for Conditions 4 and 5 (i.e., auditory suppression and somatosensory suppression) were significantly larger than the VOR gain in Condition 3 (visual suppression, $p < .001$).

The mean gain for each of the five conditions and three frequencies across subjects is shown in Table 2. Across frequencies, attending to an illuminated visual target produced, on average, 86% attenuation of the baseline VOR gain. The VOR across frequencies was reduced 28% and 31% of the baseline by directing attention toward auditory and somatosensory targets, respectively. Figure 1 shows the percent reduction in VOR gain for all five suppression conditions and for Condition 1.

Investigation 2

Method

Investigation 2 was a smaller study conducted in an effort to determine whether suppression of the VOR by nonvisual targets is additive. That is, we asked, “If we combine auditory suppression with somatosensory suppression, will the suppression effects be significantly greater than each in isolation?” The recording methods for this investigation were identical

to those as in Investigation 1, with the following exceptions: Subjects were 5 adults (2 men, mean age = 37 years) with no prior history of either otological or neurological impairments. The VOR was assessed at 0.08 Hz only, and two additional testing conditions were added to the original five conditions. In Condition 6 (imaginary visual target), subjects were asked to stare at an imaginary light moving with the chair. For Condition 7, we combined the auditory and somatosensory targets to assess whether there was an additive effect on VOR suppression. For this condition, subjects were instructed to grasp the vertical bar to which the sound source was affixed. Subjects were instructed to direct their attention to the location of their hand and sound source on the vertical bar. As in Investigation 1, the auditory stimulus was presented at 0° azimuth at a comfortable intensity (i.e., 62 dBA). Each condition (i.e., darkness with tasking, darkness without tasking, visual suppression, auditory suppression, somatosensory suppression, imaginary visual target, and combined auditory and somatosensory suppression) was replicated once, and the order of presentation of conditions was randomly assigned.

Results

Results for Investigation 2 are summarized in Table 3. Table 3 shows the mean VOR gain for each of the seven conditions for both Investigations 1 and 2. As with Investigation 1, VOR gain was greatest for Conditions 1 and 2 (darkness with and without tasking) and was smallest for Condition 3 (visual suppression). Compared with Conditions 1 and 2, the VOR gain was significantly smaller for all five suppression conditions. It is interesting to note that VOR gain was similar for Conditions 4–7 (auditory suppression, somatosensory suppression, imaginary target, and combined auditory and somatosensory suppression).

The data were analyzed with an ANOVA, where VOR gain (i.e., range of 0%–100%) served as the dependent variable and condition (seven levels) served as the grouping variable. The results revealed a significant main effect for condition, $F(6, 24) = 24.84, p < .001$.

Post hoc analysis (Bonferroni) showed that VOR gains for Conditions 1 and 2 were significantly larger ($p < .001$) when compared with all five VOR suppression conditions (range of $ps < .0001$ – $.027$). VOR gain was lowest (i.e., VOR suppression was greatest) for Condition 3 (visual suppression, $p < .001$) compared with all other conditions. The VOR gains for Conditions 4–7 were not statistically different from one another ($p = 1.0$). In other words, the VOR was suppressed to the same magnitude with attention directed toward an imaginary target as it was with attention directed toward auditory or somatosensory targets. Further, there was no additive effect of combining visual attention directed toward the auditory and somatosensory targets. As with Figure 1, for Figure 2, we used Condition 2 (i.e., VOR gain with the subject oscillating in darkness and not performing alerting tasks) as the baseline condition. As shown in Figure 2, the VOR was enhanced by 17% when the subject was performing an alerting task (Condition 1). The visual suppression condition (Condition 3) attenuated the VOR by 84%. The VOR was reduced between 34% and 44% of baseline for the other five suppression conditions.

Discussion

The objectives of the current investigation were (a) to reassess to what extent attention directed to visual and nonvisual targets can suppress the VOR, (b) to determine how comparable are the values we measure compared with those obtained from previous investigations, and (c) to determine what might be the possible origin of VOR suppression if VOR suppression occurs for nonvisual targets. Results suggested that using the unsuppressed VOR data as a baseline (i.e., Condition 2, unalerted in darkness), attention directed toward auditory and somatosensory suppressors each attenuated the VOR by 28%–44% across frequencies. However, in comparison, the magnitude of visual suppression of the VOR (i.e., Condition 3, visual suppression) was approximately two to three times greater (i.e., 84%–87% across frequencies) than the suppression achieved when subjects were attempting to stare at auditory or somatosensory targets in darkness. These findings are reasonably consistent with those reported by previous investigators (Barr et al., 1976; Furst et al., 1987; Jones et al., 1984; Moller et al., 1990). For example, visual suppression of induced nystagmus with a chair-fixed target has been reported to range from 93% to 96% (Furst et al., 1987; Moller et al., 1990). Moller et al. (1990) reported that attention directed toward a somatosensory stimulus produced on average 56% suppression of nystagmus (i.e., at frequencies 0.02 Hz, 0.08 Hz, and 0.32 Hz). The same investigators reported that attenuation of the VOR increased only slightly to 63% on average when attention was directed to a combined auditory and somatosensory target (i.e., the target was a handheld loudspeaker).

Previous investigators have suggested that an actual visual target is not required during head movement to produce a reduction in the VOR. For example, both Barr et al. (1976) and Jones et al. (1984) reported that the VOR could be attenuated during rotation in darkness when subjects were asked to fix their gaze on an imaginary visual target. That is, a real visual target was not required for attenuation of the VOR. These findings were similar to those reported by Furst et al. (1987) and Moller et al. (1990). It was the opinion of Moller et al. (1990) that their data supported the contention that modulation of the VOR was not dependent entirely on the visual system but could be potentiated by nonvisual sensory systems. The results of our second investigation showed that the VOR could be suppressed by 44% when subjects were asked to stare at an imagined visual target. This attenuation of the VOR was not significantly different from what occurred when subjects were asked to fix their gaze in darkness on a source of sound or somatosensation. Further, the suppressive effects of having multiple sensory sources to stare at were no different than those for each stimulus in isolation. Thus, these findings are consistent with the interpretation that there is a common process underlying the reduction of the VOR by gaze fixation of all targets in darkness, either visual or nonvisual.

The data in this investigation may provide us with some clues about the processes underlying VOR suppression. That is, the data would appear to support the interpretation that possibly two processes may contribute to suppression of the VOR. The first process may represent activation of other (i.e., in addition to the visual system) modality-specific (i.e., somatosensory and auditory) efferent pathways to the vestibular nuclei that inhibit the VOR. In this regard, it has been explained that corticofugal fibers destined for the vestibular nuclei

originate from the premotor cortex; the cingulate cortex; the intraparietal sulcus; the insula; the retroinsular cortex; and the posterior region of the superior temporal cortex (Akbarian, Grusser, & Guldin, 1992, 1994; Faugier-Grimaud & Ventre, 1989; Guldin, Akbarian, & Grusser, 1992; Kawano, Sasaki, & Yamashita, 1980; Leinonen, Hyvarinen, & Sovijarvi, 1980; Nishiike, Guldin, & Baurle, 2000). These are brain regions that are proximal to vestibular, somatosensory, and auditory sensory reception areas (Fukushima, 1997). Electrical stimulation of these regions has been reported to produce both inhibition and facilitation of electrical output from the vestibular nuclei (Fukushima, 1997). However, others have speculated that these cortical projections to the vestibular nuclei are predominantly inhibitory (Akbarian et al., 1994). Our data would suggest that if multisensory efferent pathways can suppress the VOR, the effect is modest (i.e., roughly one third of the magnitude of visual suppression).

A second process may represent cortical modulation of the VOR through attention directed toward a chair-fixed nonvisual target. We suggest that the effect of attention may represent a separate, nonmodality-specific process, as the magnitude of VOR suppression was not significantly different for auditory targets, somatosensory targets, imagined visual targets, or combinations of auditory and somatosensory targets. In this regard, Moller et al. (1990) also reported that the magnitude of suppression did not increase when attention was directed simultaneously toward both auditory and somatosensory stimuli (i.e., the suppressive effects were not additive). We can observe evidence of attentional effects on the VOR in the clinic during caloric testing. Attention directed toward the thermal stimulus, or the induced vertigo that follows, results in a diminution of the induced nystagmus velocity. Attention directed away from the sensation (i.e., that occurs during alerting exercises) deattenuates the induced nystagmus.

Summary

Our data are consistent with those reported by previous investigators (Barr et al., 1976; Furst et al., 1987; Jones et al., 1984; Moller et al., 1990) and suggest that it is possible for normal adults to suppress the VOR, in the absence of a visual target. That is, in addition to vision, we have shown that the VOR can be attenuated with attention directed toward chair-fixed auditory somatosensory and imagined visual targets. We suggest that this reduction in induced nystagmus may occur because of the effects of corticofugal pathways that are modality specific and destined for the brainstem vestibular center. Additionally, we believe that the data suggest that a nonmodality-specific process, such as directed attention, can explain how gaze in darkness directed toward nonvisual stimuli can result in suppression of the VOR.

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Figure 1.

Histogram illustrating the percent reduction in the maximum slow-phase nystagmus velocity for visual, auditory, somatosensory, imaginary, and combined auditory and somatosensory suppressors in Investigation 2. Condition 2 (i.e., maximum slow-phase velocity with the subject oscillating in darkness and not performing alerting tasks) served as the baseline. A positive number indicates that VOR gain was greater than baseline, and a negative number indicates the VOR was suppressed.

Figure 2.

Histogram illustrating the percent reduction in the maximum slow-phase nystagmus velocity for visual, auditory, and somatosensory suppressors in Investigation 1. Condition 2 (i.e., maximum slow-phase velocity with the subject oscillating in darkness and not performing alerting tasks) served as the baseline. A positive number indicates that VOR gain was greater than baseline, and a negative number indicates the VOR was suppressed.

Table 1.

Description of each of the seven conditions used in Investigations 1 and 2.

Condition	Description
Condition 1: Darkness with mental alerting exercises	Subjects were instructed to keep their eyes open in darkness while engaged in a mental alerting task (e.g., repeating back male and female names beginning with different letters of the alphabet). This test served as a control and as an estimate of the maximum VOR response to the oscillatory stimuli.
Condition 2: Darkness without tasking	Subjects were instructed to keep their eyes open in the dark. This condition served as a control for Conditions 3, 4, and 5.
Condition 3: Visual target	Subjects were instructed to keep their eyes open while staring at a chair-mounted red laser light in the dark (i.e., visual suppression of the VOR).
Condition 4: Auditory target	Subjects were instructed to keep their eyes open while staring at, and listening to, a digital sound recorder (Sony IC Recorder), playing “Moonlight Sonata” by Beethoven, at a level of 62 dBA 0° azimuth in the dark. The recorder was attached to the top of the vertical bar.
Condition 5: Somatosensory target	Subjects were instructed to keep their eyes open in darkness while grasping with both hands and staring at the vertical bar mounted on the footplate of the rotary chair.
Condition 6: Imaginary visual target	Subjects were instructed to keep their eyes open and gaze straight ahead at an imaginary light.
Condition 7: Combined auditory and somatosensory target	Subjects were instructed to keep their eyes open and both listen to the auditory stimulus (same stimulus as in Condition 4) and grasp the vertical bar to which the sound source was affixed (same vertical bar as in Condition 5). Subjects were instructed to direct their attention to the location of their hand and sound source on the vertical bar.

Note. VOR = vestibulo-ocular reflex.

Table 2.

Mean VOR gain (*SD*) for each of the five conditions and three frequencies in Investigation 1.

Condition	Frequency (Hz)			
	0.02 Hz	0.08 Hz	0.32 Hz	Three-frequency mean
1 (Darkness with alerting)	43.1 (12.6)	49.2 (16)	51.2 (18.6)	47.8 (15.9)
2 (Darkness without alerting)	39.8 (8.9)	48.7 (11.3)	45.8 (14.7)	44.7 (12.2)
3 (Visual suppression)	6.2 (2.8)	6.4 (1.5)	6.7 (4)	6.4 (2.9)
4 (Auditory suppression)	31.8 (10.2)	35.1 (12.4)	32.4 (15.3)	33.1 (12.60)
5 (Somesthetic suppression)	32.2 (9.8)	33.4 (12.4)	32.3 (13.7)	32.6 (11.80)

Table 3.

Mean VOR gain (*SD*) at 0.08 Hz shown for all conditions in Investigations 1 and 2.

Condition	VOR gain: Investigation 1 (<i>n</i> = 16)	VOR gain: Investigation 2 (<i>n</i> = 5)
1 (Darkness with alerting)	49.2 (16.0)	56.3 (8.9)
2 (Darkness without alerting)	48.7 (11.3)	47.8 (7.9)
3 (Visual suppression)	6.4 (1.5)	7.2 (1.8)
4 (Auditory suppression)	35.1 (12.4)	31.2 (6.1)
5 (Somatosensory suppression)	33.4 (12.4)	25.9 (7.7)
6 (Imaginary target)	N/A	31.6 (7.8)
7 (Combined auditory and somatosensory)	N/A	26.4 (7.5)

Note. N/A = not applicable.