Review Article

Effects of Visual Input Changes on Canal and Otolith-Dependent Vestibulo-Ocular Reflexes: A Review Study

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Highlights

- Changes in visual inputs can lead to different changes in the vestibulo-ocular reflex
- The changes in visual inputs lead to a slight to severe transformation in the VOR
- These transformations depends on the time course, severity and duration of changes

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ABSTRACT

Background and Aim: There is an integration between visual and vestibular systems. Changes in visual inputs can result in different changes in the Vestibulo-Ocular Reflex (VOR). This review study investigate the changes in VOR due to changes in visual inputs. In this regard, the effects of different conditions such as visual deprivation, changes in visual acuity, visual-vestibular conflict, and binocular vision dysfunction on VOR were assessed.

Recent Findings: Changes in visual inputs and visual-vestibular conflicts can lead to different changes in VOR.

Conclusion: The changes in VOR effects vary from slight to severe transformation dependent on the time course, severity and duration of changes in visual inputs.

Keywords: Vestibulo-ocular reflex; visual inputs; refractive errors; head impulse test

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Introduction

There is an integration between the sensory, visual and vestibular systems [1]. Vestibulo-Ocular Reflex (VOR) consists of three-neurons reflex arc that connects the vestibular system to oculomotor neurons in the brainstem. These pathways are under the influence of visual inputs [2]. The VOR is initiated from the sensory organs of the vestibular system; the semicircular canals, and otolith organs. Each of these receptors is sensitive to a different kind of movements. The semicircular canals react to angular acceleration (rotation) of the head and body in different planes, while otolith organs (utricle and saccule) are responsible for sensing linear acceleration such as waking or riding in an elevator. Based on these receptors, there are rotational and linear VOR pathways that are responsible for maintaining a fixed gaze. The VOR pathways include vestibular organs, superior and inferior vestibular nerves, vestibular nuclei, and oculomotor nuclei. Each pathway depends on individual vestibular organs. For example, they are different neural pathways for three semicircular canals but they include medial longitudinal fasciculus, ventral tegmental tract, and ascending tract of Dieters for angular excitatory projections and medial longitudinal fasciculus for angular inhibitory projections [2]. VOR causes slow-phase ocular movements with almost the same speed but in a direction opposite to head movements; therefore, gaze remains stable and visual acuity is sustained [2]. The VOR is capable of adaptation to changes in environmental requirements that is needed during different stages of life. It may happen faster under conditions similar to wearing new glasses for the first time or happen gradually for a long period due to changes in sensory and vestibular organs while growing older. Damage to the vestibular system can also affect the VOR [3]. Various conditions such as using lenses can affect visual inputs in people with normal vestibular function and cause retinal slip and gaze unsteadiness with head movement [4]. Continuous retinal slip results in neural mechanisms that are responsible for VOR changes [5]. In addition, a mismatch between the vestibular stimulus and the visual target causes alterations in the VOR [4]. Reduction [6] or deprivation [7, 8] of visual inputs can also cause substantial changes in this reflex. Some important vestibular tests such as video Head Impulse Test (vHIT) and ocular Vestibular-Evoked Myogenic Potential (oVEMP) are used for evaluating the VOR where different visual inputs may affect their results. The parameters of gain, asymmetry and catch-up saccades (overt and covert) in vHIT and the parameters of latency and amplitude ratio of waves in oVEMP are usually used. This study aimed to evaluate the changes in VOR in response to variations in visual inputs reported in various studies.

Methods

In this review study, a search was conducted for the related studies in different databases such as Web of Science, PubMed, Scopus, SID, Magiran, and Google Scholar, published from 1974 to 2021 using the keywords: Vestibulo-ocular reflex, adaptation, visual inputs, visual acuity, refractive errors, spectacles, ocular vestibular-evoked myogenic potential, and head impulse test. Inclusion criteria were the study on VOR and conducting vestibular evaluations following changes in visual conditions (e.g. using optical devices) or alterations in visual inputs. The studies in which the VOR adaptation and any variations in this reflex occurred solely due to pathologic vestibular or neurologic causes or factors irrelevant to visual system were excluded. Initial search yielded 66 articles, of which 48 were selected based on the inclusion and exclusion criteria, in which changes in visual inputs affected the VOR.

Results

The results of studies regarding the effects of visual inputs on VOR in different conditions are presented in this section.

Effects of visual deprivation on vestibulo-ocular reflex

Visual inputs are highly important in maintaining normal function of different types of eye movements [8] and normal development of VOR [9, 10]. The results of different studies about the effects of visual deprivation are summarized in Table 1. Many studies on animal models grown in darkness and the blind human models indicate the effect and importance of visual inputs in appropriate development and function of VOR [7-11]. The notable point in these studies was the importance of the time course that blindness occurred and the visual experience before visual loss. VOR in congenitally blind humans showed the most severe effects and attenuations [7, 8]. As the time of blindness onset was delayed and the subjects had visual experiences for a longer period, the intensity of the effects decreased. People who became blind in later stages of life, had normal VOR [7]. The finding in a recent study using the vHIT test in blind people also showed decreased VOR gain and more frequent catch-up saccade compared to people with normal vision. The loss in VOR gain was observed in vertical

Table 1. The results of different studies about deprivation of visual inputs on vestibulo-ocular reflex in different animals and subjects

Authors	Year	Subject/animal	Goal/method	Main findings
Berthoz et al. [9]	1975	Cat	Deprivation, cats raised in darkness and comparison with normal ones	Low frequency of nystagmus in the cats raised in darkness, reduced VOR gain
Harris and Cynader [10]	1981	Cat	Deprivation, cats raised in darkness and comparison with normal conditions	VOR gain was substantially decreased in the cats raised in darkness until 11 to 15 months of age
Collewijn [11]	1977	Rabbits	Deprivation, rabbits raised in darkness for 7 months after birth	Considerable VOR gain reduction
Leigh and Zee [8]	1980	Human	Comparing electrooculography and motion pictures findings of VOR responses in congenital and acquired blindness	VOR was absent or severely diminished in subjects with congenital blindness, and VOR responses were comparatively well-maintained in acquired blindness, resemblance between ocular movements in the blind subjects and patients suffering from cerebellar injuries
Kömpf and Piper [7]	1987	Human	Electronystagmography evaluations in another study indicated the absence of VOR in subjects with different types of blindness	Absence of VOR in subjects with congenital blindness. An extended deprivation after development of visual system, can only diminish VOR and is not able to completely extinguish it. A loss of vision that has occurred for a short time, does not have a considerable influence on VOR
Chihara et al. [12]	2009	Human	Results of the oVEMP test in subjects whose orbital contents were unilaterally enucleated due to malignant tumors and comparing the results with patient whose left eyeball was enucleated following an injury but the extraocular muscles were kept and could move his artificial eye	Essential role of extraocular muscles in the generation of oVEMP responses. However, removing the eyeball solely did not have an important effect on the VOR responses
Bayram et al. [13]	2018	Human	Comparing the oVEMP responses in subjects with long unilateral acquired blindness with normal subjects	Normal oVEMP responses on the 93.5% unilaterally blind patients. oVEMP responses including latency and amplitude on the blind side were not statistically different when compared with the unilaterally blind subjects' normal eyes or normal subjects' eyes. There was no statistical difference in the amplitude asymmetry ratio between the two groups. oVEMP responses can be obtained in a blind eye as long as the eyeball and extraocular muscles are maintained
Rosengren et al. [14]	2005	Human	A patient who underwent craniofacial resection and the eye and extraocular muscles were enucleated in the right side, was examined with the oVEMP test	Short latency negative potentials were elicited in both eyes. The necessity of the presence of eyeball and extraocular muscles for acquiring oVEMP response
Chihara et al. [15]	2007	Human	Effect of closing eyes on the results of the oVEMP	The prevalence of responses was lower when the oVEMP tests was done with closed eyes compared with open eyes
Huang et al. [16]	2012	Human	Results of the oVEMP test with closed eyes in comparison with open eyes and an upward gaze	The latencies and N1-P1 intervals were significantly longer and the N1-P1 amplitudes were significantly lower but mean amplitude asymmetry ratio was not affected considerably
Todai et al. [17]	2014	Human	Effect of closing eyes on the results of the oVEMP	Diminished oVEMP responses noticed in latencies, amplitudes and thresholds under eyes-closed condition and responses that could be recorded in a very lower number of subjects
González et al. [18]	2018	Human	The effect of milder degrees of deprivation of visual inputs on VOR, Patients suffering from age-related macular degeneration with loss of central vision and subjects with normal vision were evaluated in light and dark in order to assess the effect of eccentric viewing on this reflex	The measured VOR gains were higher when the eyes moved leftwards in a significant number of patients which indicated that an eccentric area of retina located at the left side of the scotoma was used as a new reference point for ocular-motor system. There was no asymmetry in the results of subjects with normal vision

semicircular canals [19]. In another study on blind and practically blind people, the visual acuity and duration of blindness had a significant effect on vHIT results. The authors did not come to a conclusion that the vHIT is a reliable test for evaluating vestibular system in people with blindness even with the new acoustically enhanced method [20].

The duration of visual deprivation had also a crucial effect on VOR responses. The congenital visual deprivation was reported to have a very strong effect on VOR responses and reducing the VOR gain. Eye movements were more affected in cats grown in darkness until the age of 11-15 months [10] compared to those grown in darkness until the age of 4 months [11], indicating the importance of the duration of visual deprivation. On the other hand, acquired blindness only reduced the VOR responses that were dependent on the duration of blindness. However, even the closed eyes under the oVEMP test could affect the responses. Unavailable visual inputs may be one of the possible reasons for why the oVEMP test results were attenuated under the eyes-closed condition [15-17]. In summary, it can be said that the VOR gain is severely affected in congenitally blind people but the effects in those with acquired blindness are mainly related to the duration of blindness.

Effect of visual acuity on vestibulo-ocular reflex

There are few studies on the effects of visual acuity on VOR, evaluated mainly by vHIT and Dynamic Visual Acuity Test (DVAT). Participants in a study were categorized in three groups of normal vision, uncorrected refractive errors, and visual impairment, considering the visual acuity of their better eye. Subjects with uncorrected refractive errors and visual impairment had worse balance in Romberg test [6]. The effect of visual acuity on the VOR using the vHIT was also investigated in some studies [21, 22]. There was no correlation between subjects' visual acuity and the amount of VOR gain based on the vHIT results [22]. Judge et al. found that visual acuity had no effect on the results of vHIT test including VOR gain, corrective saccade frequency, and amplitude [21]. Another study indicated that refractive errors and wearing glassess [23] had no effect on the vHIT results. The recent studies on visual acuity showed no effect on the VHIT results; however, the results of other VOR tests may be different. For instance, the results of DVAT are related to several factors such as target distance and head movement velocity, continuous range of vision and especially static visual acuity [24].

Effect of visual-vestibular conflict on vestibulo-ocular reflex

Different conditions can cause visual-vestibular conflict that may affect the VOR especially when these conditions are long term. For example, in early studies it was demonstrated that wearing reversing prisms can result in VOR gain loss in human subjects [25]. In studies on the long-term effects of vision reversal with prisms, VOR gain was reduced significantly in the first days and roughly reversed in the last days [26]. There were also some studies on the effects of optokinetic stimuli on the Subjective Visual Vertical (SVV) test. The clockwise or counter-clockwise rotation of optokinetic stimulus caused a significant additional shift even in subjects with normal vision [27, 28]; the direction of preset angle and visual background rotation had also some significant effects [29]. Table 2 summarizes the different effects of visual-vestibular conflict on VOR.

Some studies evaluated the effects of visual-vestibular conflict on VOR and demonstrated VOR adaptation [1, 22, 25, 26, 30-42]. Optical devices including reversing prisms, telescopic spectacles, and normal-looking spectacles were used to create a conflict between the vestibular stimulus and the visual target. Increases and decreases in VOR gain and the reversal of this reflex indicates that the VOR has adaptation to changes and can minimize retinal slip when visual inputs are changed. For instance, when subjects wear magnifying spectacles, they perceive a higher amount of movement in what they see and thus need a higher amount of VOR movement. The signal regarding image motion on the retina is transmitted to vestibulocerebellum. Then, Purkinje cells send impulses to the vestibular nucleus which affects the sensitivity of floccular target cells to vestibular inputs [4]. It is assumed that when people are under conditions in which a stimulus is provided for visual-vestibular conflict in an long period, synaptic and neural changes occur in the direct VOR circuit [43]. Visual inputs are of high importance in preserving VOR precision; reduction in these inputs may diminish VOR gain [44-46].

The animal studies [30-35] displayed the important role of flocculus and vestibulocerebellum in the process of VOR and visual-vestibular adaptation. The studies that used different spectacles showed the prismatic effects. These effects occurred by wearing spectacles and resulted in high or low amounts of eye movements required to make up a certain amount of head movement in the reverse direction. Hence, the VOR experienced some changes. However, there were studies that reported no prismatic effects (and no visual-vestibular conflict)

Table 2. The different effects of vestibular-visual conflict on vestibulo-ocular reflex in different animals and subjects

Authors	Year	Subject/Animal	Goal/method	Main findings
Ito et al. [30]	1974	Rabbit	VOR adaptation as a result of vision reversal presenting a stationary and moving light during head turn	Stationary light during head turn increased VOR gain and moving light during rotation decreased VOR gain. Created a condition similar to vision reversal. VOR reversal was also observed Significant influence on VOR following destruction of paraflocculus, the whole right cerebral cortex or the cerebellar visual areas but not left cerebellar flocculus
Jones and Davies [31]	1976	Cat	VOR adaptation as a result of vision reversal effects of using reversing prisms for 200 days	As the vision reversal began, VOR gain was reduced and functional inversion of VOR was finally noticed when it was evaluated in the dark
Robinson [32]	1976	Cat	VOR adaptation as a result of vision reversal Using reversing prims	Reduced VOR gain and inverted the direction of eye movements Removal of vestibulocerebellum from the cerebellum increased VOR gain to 1.17 in the dark and all the changes caused by using prisms disappeared
Miles and Eighmy [33]	1980	Monkey	VOR adaptation as a result of vision reversal by wearing telescopic spectacles and other optical instruments were used to alter visual inputs	VOR gain elevation and reduction. Fixed field spectacles diminished VOR considerably and the gain was reduced. VOR adaption also occurred as a result of wearing reversing prisms
Freedman et al. [34]	1990	Cat	Wearing telescopic spectacles, optokinetic drum, 2.2x telescopic spectacles and 2.1x Fresnel telescopic lenses were used as 3 different ways	Increase VOR gain, the increase in VOR gain following using Fresnel lenses was higher and steadier
Miles and Fuller [35]	1974	Monkey	Wearing telescopic spectacles, passive oscillation in the dark and eye movements were evaluated with electrooculography. 2x telescopic spectacles	VOR adaptation, increase in VOR gain while 0.5x telescopic spectacles decreased the gain
Demer et al. [36]	1987	Human	The short-term influences of wearing 2.2x telescopic spectacles on VOR was evaluated and after 15 minutes of rotation while wearing the telescopic spectacles	VOR underwent changes including an increase in gain in the dark in and magnified vision
Demer et al. [37]	1989	Human	Subjects were rotated sinusoidally for 15 minutes while wearing 2x, 4x, and 6x binocular telescopic Spectacles with occluded peripheral visual fields that were not magnified and eye movements were recorded with electrooculography	There was a significant elevation of VOR gain (7–46%) in 47–70% of participants. The amounts of changes in gain were Considerably reduced when the unmagnified peripheral visual field was no longer occluded throughout the experiment. The mean VOR gain measured after doing the experiment with 4x telescopic spectacles without occlusion of peripheral visual field was not significantly different than the initial amount of the gain in 8 subjects
Gauthier and Robinson [38]	1975	Human	VOR adaptation after using 2.1x telescopic spectacle with occluded peripheral visual field, VOR was evaluated by rotation and eye movements were recorded with electrooculography	VOR gain was elevated after 5 days
Istl-Lenz et al. [39]	1985	Human	VOR adaptation after using telescopic spectacles	VOR adaptation and a change in VOR gain
Collewijn et al. [40]	1983	Human	Lower degrees of vestibular-visual conflict including using magnifying and minifying spectacles of +5.00 and –5.00 diopters	VOR adaptation was observed
Michaelides and Schutt [41]	2014	Human	Wearing contact lenses	No prismatic effects because of changing the position of lenses with the eyes mathematical modelling and calculations in a study indicated that different amounts of eye rotation and VOR gain are needed in areas having different heights in a progressive lens

Authors	Year	Subject/Animal	Goal/method	Main findings
Cannon et al. [42]	1985	Human	Results of VOR evaluations with electrooculography and rotational chair testing when the subjects were accustomed to wearing spectacles	Lower and higher amounts of VOR gain in myopic and hyperopic subjects respectively
Li et al [22]	2015	Human	The effects of magnifying lenses used in presbyopic subjects on the results of VOR evaluations with EyeSeeCam Video-oculography	Magnification of the spectacles had an influence on VOR gain
Thakar A [1]	2016	Human	The results of caloric tests were compared between myopic and emmetropic subjects	Hypoactive responses in myopic spectacle wearers were substantially more common than in emmetropic subjects
van Dooren et al. [23]	2018	Human	Wearing spectacles on a daily basis, VOR gain measured with the VHIT test	No influence on the VOR gain between three groups of subjects with normal vision and subjects wearing spectacles and contact lenses. The amounts of VOR gain and refractive error were not significantly associated when the head was turned rightwards or leftwards

when subjects wore contact lenses because the position of these lenses changes with the eye movement. These studies showed that any condition that cause visual-vestibular conflict may affect the VOR.

Effect of binocular vision dysfunction

Binocular vision dysfunction refers to any condition that can cause the eyes to become misaligned and the eyes cannot create one clear binocular image. This is a common phenomenon that occurs in some patients. The VOR changes in response to binocular vision dysfunction have been reported in some studies [40, 47, 48]. Table 3 presents the results of these studies. Sensory and motor mechanisms are involved in binocular vision. The motor mechanism adjusts the direction and position of the eyes to place the image of a target on the two foveae. Conjugate eye movements including VOR eye movement, are a part of this mechanism [49].

Conclusion

The changes in visual inputs vary from visual deprivation and visual-vestibular conflicts to reduction in visual sensitivity. In the most cases, changes in visual inputs lead to changes in VOR gain. The vHIT results are somehow resistant to some of these effects. The reviewed studies showed that the change in visual acuity, visual-vestibular conflict and binocular vision dysfunc-

Table 3. The effects of disruption in binocular vision on vestibulo-ocular reflex

Authors	Year	Subject/Animal	Goal/method	Main findings
Viirre E, et al. [48]	1987	Monkey	Occluding one eye in for a week	Alterations in saccadic eye movements and VOR in the occluded eye. The function of the occluded eye returned to the normal state a day after the occlusion was ended and the function of the other eye was not affected
Collewijn et al. [40]	1983	Human	Placing a lens of -5 diopters in front of a subject's right eye and occluding the other eye for 24 hours	VOR adaptation and reduction in VOR gains of the two eyes
Sehizadeh [47]	2005	Human	The effect of a combination of a spectacle and contact lenses causing aniseikonia for 4 hours, image was magnified in the right eye and minified in the left eye by lenses of +5.00 and –5.00 diopters placed in the spectacle, respectively. The contact lenses provided the power needed for compensating the subjects' usual correction and the blurred vision caused by the spectacle lenses	VOR gain was significantly reduced only in the left eye instantly after the combination was removed and it was reduced in both eyes in the evaluations done every 30 minutes following the removal of the combination for 2 hours. Monocular adaptation of VOR occurred
van Dooren et al. [23]	2018	Human	The results of VHIT test was compared between binocular and monocular conditions	The results of VOR evaluations were not significantly different

tion do not affect the VHIT results. However, in other tests, the changes in visual inputs can lead to changes in VOR gain.

Ethical Considerations

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Authors' contributions

JHS: Study design, interpretation of the results, drafting and revising the manuscript; MM: Acquisition of data, drafting the manuscript; SJ: Study design, interpretation of the results, drafting and revising the manuscript.

Conflict of interest

No potential conflict of interest relevant to this article was reported.

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