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RESEARCH ARTICLE

Enhanced vestibulo-ocular reflex suppression in dancers during passive high-velocity head impulses

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Abstract

The vestibulo-ocular reflex (VOR) is responsible for stabilizing images on the fovea during head movements. However, in some situations, one needs to suppress the VOR to be able to follow a target moving along with the head. Evidence suggests that the visual mechanism underlying VOR suppression can be modulated by experience. Unfortunately, the non-visual mechanism underlying VOR suppression has never been examined in dancers and, consequently, it is still unsure whether dance training can enhance eye-head tracking accuracy. The goal of the present study was to look at the influence of dance training on the VOR suppression during passive head impulses. Twenty-four individuals participated, 12 controls and 12 dancers. VOR and VOR suppression were assessed using a head impulse paradigm as well as a suppression head impulse test paradigm (SHIMP) with video head impulse test, respectively. The results suggest that dancers display a significantly reduced VOR gain during the SHIMP at 60 ms in comparison to controls. Moreover, dancers with more than 10 years of dance training exhibited a significantly reduced VOR gain during the SHIMP at 60 ms. Overall, the results suggest that dance training improves VOR suppression, but also modulates VOR suppression abilities. Although studies are needed to shed light on the possible mechanisms involved in the modulation of the VOR gain, the observed changes in dancers' vestibulocerebellum and its role in the modulation of the VOR gain makes the cerebellar–vestibular nuclei pathway a possible model to explain the present results.

Keywords Vestibular · Vestibular–ocular reflex · Dance · Video head impulse test

Introduction

The vestibular system contributes to a wide variety of different vestibular processes ranging from basic reflexes to higher cognitive functions (Angelaki and Cullen 2008; Smith and Zheng 2013). One of these reflex pathways is the vestibulo-ocular reflex (VOR). The VOR is responsible for stabilizing images on the fovea during head movements by moving the eyes at equal velocity—but in a direction that is opposite to that of the head movements. This reflex consists of a three-neuron arc where primary vestibular afferents project to vestibular nuclei, which in turn project to oculomotor neurons, thereby allowing the control of the extraocular muscles (Cullen 2016). The simplicity of the VOR pathway makes it very fast; indeed, it occurs as early as 5–6 ms after a stimulus onset (Angelaki and Cullen 2008).

However, when one is required to follow a target that moves with the head, like looking at a car passing by or keeping one's eyes focused on a moving ball, the VOR may be counterproductive and, therefore, it would need to be suppressed or canceled. If not, the eyes would be moving in a direction that is opposite to that of the head and of the visual target. It has been suggested that VOR suppression during passive head impulse normally occurs around 80–90 ms (Crane and Demers 1999). The mechanism involved in VOR suppression seems to depend on the velocity of the target. The visual mechanism usually occurs at velocities under 60°/s, as it involves saccades and smooth pursuit pathways (Buizza and Schmid 1986; Cullen et al. 1991). Above this velocity, the visual mechanism would not be accurate. A

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second mechanism, the non-visual mechanism, produces a signal that is related to ongoing head movements, making it possible to cancel the VOR signal or to reduce the sensitivity of the VOR pathways during head movements (Cullen and McCrea 1993). This non-visual mechanism is critical to extend eye-head tracking range and accuracy during high-velocity (Cullen et al. 1991).

There is evidence suggesting that the VOR might not be a hard-wired reflex and, thus, that it can be modulated by experience (Roy and Cullen 1998). Indeed, a few studies have examined the ability to suppress nystagmus induced by vestibular stimulation in participants undergoing repetitive vestibular-related training, namely, dancers. These studies compared dancers' and non-dancers' (i.e., controls) ability to suppress nystagmus following whole-body rotation or caloric vestibular stimulation (Osterhammel et al. 1968; Teramoto et al. 1994). Following vestibular stimulations, the participants had to suppress their nystagmus by staring at an earth-fixed visual target. The results showed that dancers were better than the controls to suppress their nystagmus, suggesting that dancers are able to modulate their VOR response. Moreover, Teramoto et al. (1994) found a significant correlation between dancers' experience and rate of VOR suppression, thus suggesting that dancers' suppression rate could be a good indicator of their experience. More recently, Tanguy et al. (2008) revisited the evaluation of VOR during passive sinusoidal rotations. They observed that, during rotations in complete darkness (without visual target), dancers revealed a significant reduced VOR gain as opposed to non-dancers. These previous studies support the hypothesis that VOR and VOR suppression can be modulated through experience and training. However, these studies evaluated either the capacity to suppress VOR following or during vestibular stimulation at velocities under 60°/s. To date, the ability to suppress VOR during high-velocity (above 60°/s) has not been tested. Therefore, the possible role of training on the modulation of the non-visual mechanism underlying VOR suppression remains unknown.

The main goal of the present study was to evaluate the effect of dance training on VOR suppression during passive head impulse tests. Based on previous literature, the dancers should exhibit reduced VOR gains earlier than the non-dancers during the VOR suppression task. Moreover, more dance training should lead to a greater reduction in VOR gain.

Methodology

Participants

Twenty-four participants, 12 dancers and 12 controls (i.e., non-dancers), were included in the present study. The groups did not differ significantly on age, weight, and height. All of the participants reported to be healthy and to have normal or corrected-to-normal vision. None of the participants had a history of concussion or ear surgery. The dancers' average length of dance training was 9.2 years (2.5–20 years). Dancers were practicing 16.6 h/week, on average (3–30 h/week). All the dancers were still practicing dance actively and rated themselves as being advanced or expert dancers. The participants in the control group were not practicing competitive sports. The present study was approved by the ethic committee of the Université de Montréal (CERES).

Protocol

All the participants underwent a head impulse (HIMP) test of the horizontal semi-circular canals followed by a suppression head impulse test (SHIMP) using the video head impulse test (vHIT-Eyesee cam, Interacoustics, Denmark). The protocols used for the HIMP and SHIMP tests were based on MacDougall et al. (2016). The infrared camera was mounted on the goggle frame to record the right eye at a frame rate of 250 Hz. The positions of the eyes and head movements were calibrated for each participant before performing impulses.

During the HIMP test, participants were sitting 1 m away from an earth-fixed target (fixed on the wall). They were asked to keep their eyes on the target while the experimenter was inducing unpredictable horizontal head impulses with a velocity ranging from 150 to 250°/s. A total of seven HIMPs were performed on each side of participants' head. The SHIMP protocol was similar to the HIMP protocol, with the exception that, in the SHIMP protocol, the participants had to stare at a head-fixed target that was projected on the wall through a laser mounted on vHIT goggles. Particular care was taken to avoid goggle slippage and to reduce artifacts.

The analysis of gain was made within 100 ms following the head impulse (see Fig. 1) to reduce the contribution of the cervico-ocular reflex and pursuit, which have latencies above 100 ms (Bronstein and Hood 1986; Carl and Gellman 1987). For both HIMP and SHIMP tests, the instantaneous gain was retrieved for each participant at 40, 60 and 80 ms. To do so, the ratio of the eye velocity on the head velocity was calculated for the specific data obtained at 40, 60, 80 ms for each trial on the right and each trial on the left. Finally, the mean gain of the seven trials on the right and the seven trials on the left were averaged. Statistical analyses were performed, for each test, using the average gain of the right and left impulses—this at each of the three latencies (40, 60, and 80 ms).

The head and eye velocity traces were visually inspected for artifacts before performing any gain analysis based on McGarvie et al. (2015). The head traces had to be free of any movements prior to impulse and have an abrupt stop with

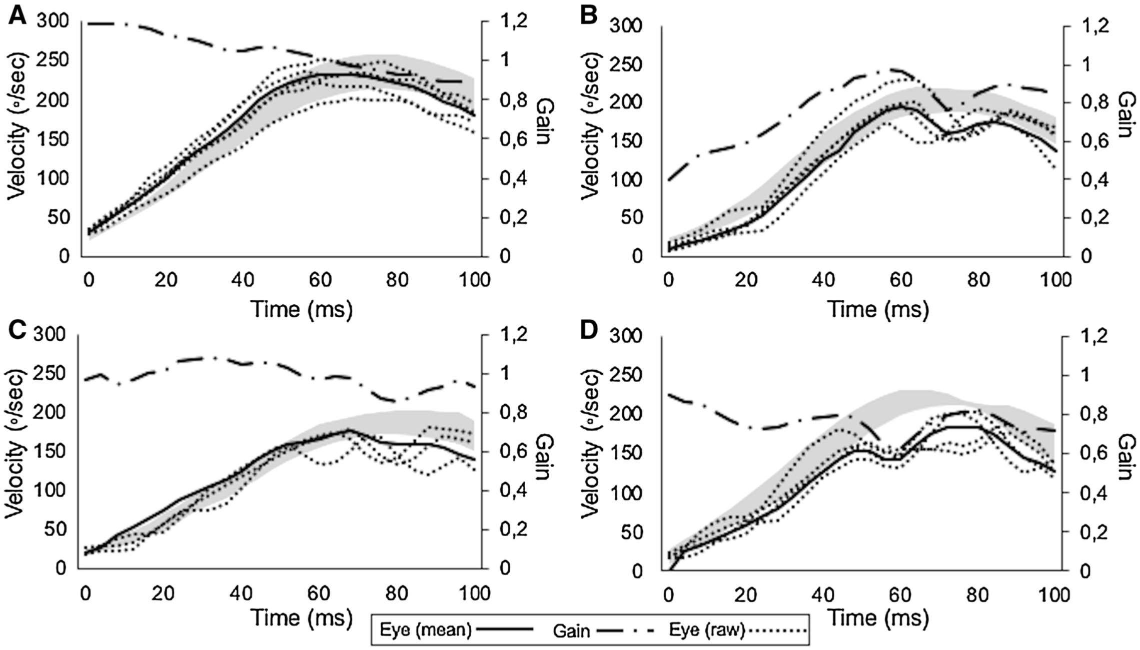

Fig. 1 Representation of mean eye velocity (solid line), head velocity (±1 standard deviation represented by shaded area), eye velocity curve of each impulse (dotted line) and average gain (dash line) for the first 100 ms during head impulse. **a, b** Represent respectively HIMP and SHIMP of a control subject. **c, d** Represent, respectively, HIMP and SHIMP of a dance trained subject

as little “bounce-back” as possible. The eye velocity traces containing any eye movement prior to impulse and any obvious google movement or eyelid artifacts were eliminated.

Data analysis

Gain differences between dancers and non-dancing controls at 40, 60, and 80 ms were analyzed using a one-way multivariate analyses of variance (MANOVA). Moreover, to assess the impact of length of dance training on SHIMP response, a one-way ANOVA was performed. To do so, the participants were divided in three groups, namely, controls ($n=12$) without any dance experience, dancers who had been dancing for less than 10 years ($n=7$), and dancers who had been dancing for more than 10 years ($n=5$). The participants’ SHIMP response was compared at three different latencies (40, 60, and 80 ms). A Post hoc Tukey correction factor for multiple comparisons was performed when necessary.

Results

First, the results of the MANOVA on HIMP revealed a significant group difference [$F(3,20)=4.31$, Pillai $=0.39$, $p=0.017$ $\eta_p^2=0.393$)]. However, no significant difference was observed between groups for the HIMP protocol and this at any of the three latencies (40 ms: $F(1,22)=2.857$, $p=0.105$ $\eta_p^2=0.115$; 60 ms: [$F(1,22)=0.087$, $p=0.770$ $\eta_p^2=0.004$]; 80 ms: $F(1,22)=3.358$, $p=0.080$ $\eta_p^2=0.132$; see Fig. 2a). For the SHIMP test, a MANOVA revealed a significant group difference [$F(3,20)=3.154$, Pillai $=0.32$, $p=0.047$ $\eta_p^2=0.321$)]. Post hoc analysis revealed significant differences in gain between the groups only at 60 ms [$F(1,22)=8.05$, $p=0{,}01$ $\eta_p^2=0.268$)] revealing a higher gain for the controls than the dancers (dancers: $M=0.77$; controls: $M=0.85$; see Fig. 2b). No significant differences were found between the groups at 40 ms and 80 ms [40 ms: $F(1,22)=0.136$, $p=0.72$ $\eta_p^2=0.006$]. ; 80 ms: [$F(1,22)=0.06$, $p=0.81$ $\eta_p^2=0.003$)].

The results of the analysis of the effect of dance training length revealed significant differences between the groups [$F(2,21)=4.09$, $p=0.03$] (Fig. 3). Post hoc Tukey analysis was performed and revealed a significant difference between controls and dancers with more than 10 years of experience only at 60 ms ($p=0.049$). In line with our hypothesis, no significant differences between the groups were found on the SHIMP test at 40 ms and 80 ms or for HIMP test, this at any given latency. Finally, no significant differences were observed between dancers with less than 10 years of dance training as compared to any other groups.

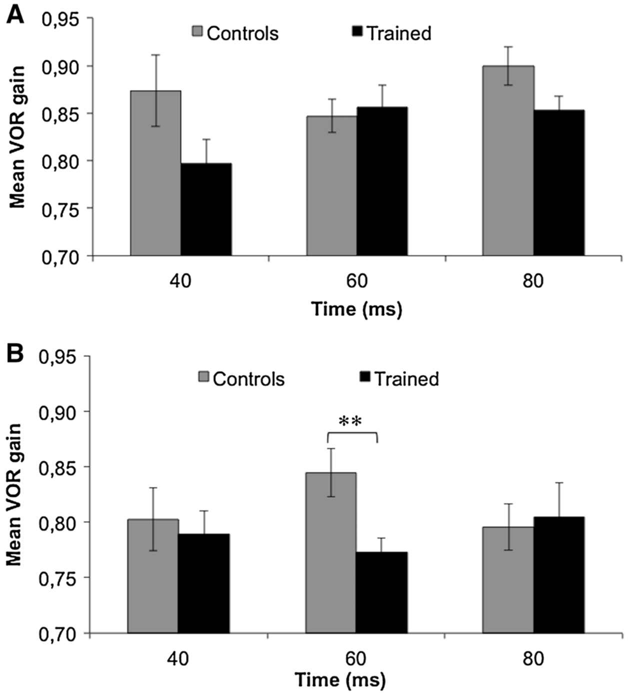

Fig. 2 Comparison of mean VOR gain between controls (gray) and dancers (black) during HIMP (**a**) and SHIMP (**b**). Significant difference between groups is observed only for SHIMP at 60 ms ($p \leq 0.01$)

Discussion

The goal of the present study was to evaluate the effect of dance training on the VOR and on VOR suppression during passive high-velocity head impulse tests. To do so, the participants were assessed using a head impulse paradigm (HIMP) as well as a suppression head impulse paradigm (SHIMP)—using the video head impulse test. The results show that both groups had similar results with regard to the HIMP, but also that they differed significantly on the SHIMP. Indeed, both groups were able to suppress the VOR during passive high-velocity head impulses, but more importantly, the dancers were able to do so earlier than the controls. Specifically, we found that the VOR gain in dancers at 60 ms was significantly lower than that of the controls, suggesting that the dancers can modulate more efficiently their VOR. No significant group differences were found at 40 ms and 80 ms. The absence of significant differences at 80 ms may suggest that both groups were able to suppress the VOR equally, thus supporting previous evidence in showing that, in normal healthy adults, the suppression of the VOR during unexpected passive rotations usually occurs around 80 ms (Crane and Demers 1999).

Our results also suggests that the length of dance training is associated with enhanced VOR suppression abilities as only people who have been dancing for more than 10 years have a significantly reduced VOR gain at 60 ms as opposed to controls. These last results must however be interpreted cautiously given the small number of participants who had more than 10 years of dance training ($n = 5$). Individual data in Fig. 2 reveal that even dancers with less then 10 years of experience tend to differ (not significantly) from controls. Then, lack of significant difference may be due to the small number of participants in the present study. In future studies, a larger group of participant could help us to determine whether long-term dance training is necessary to influence VOR suppression.

Numerous neural substrates at different hierarchical processing levels might explain dancers' enhanced performance in VOR suppression. First, at the level of the vestibular nuclei, two types of neurons are involved in the VOR pathway: (1) eye-head neurons (EH) and (2) position-vestibular-pause (PVP) neurons. EH neurons are known to receive strong projections from Purkinje cells within the floccular

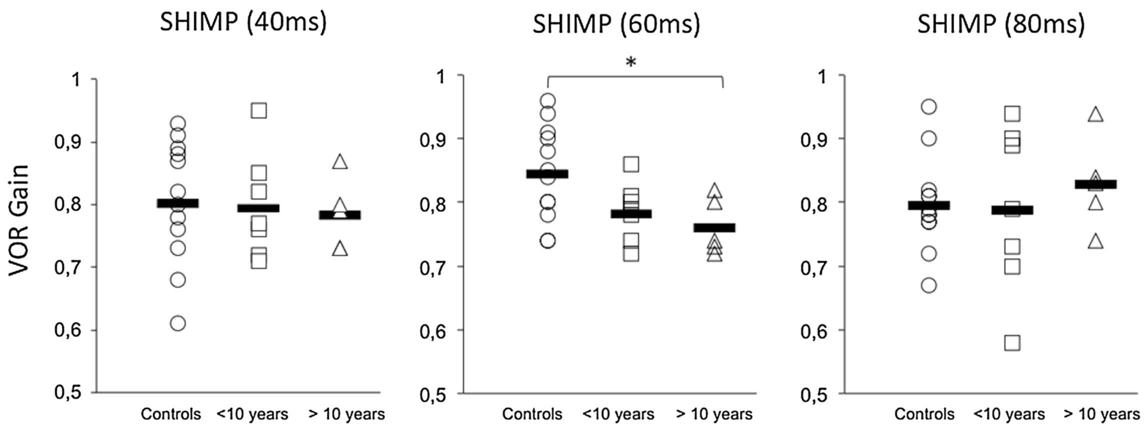

Fig. 3 VOR gain during SHIMP at 40, 60 and 80 ms in relation to dance training experience. Dancers with more than 10 years of experience had a significantly lower gain at 60 ms during SHIMP as opposed to controls ($p \leq 0.05$)

lobe of the vestibulo-cerebellum and to project to extraocular motor neurons (Mitchell et al. 2016). The Purkinje cells within the vestibulo-cerebellum were found to carry the signals of head and eye velocity. It has been proposed that, during a VOR suppression task, a head velocity signal could act as an inhibitory side loop to cancel VOR (Ito 1982). In line with this previous study, the enhanced VOR suppression observed in dancers might originate from an adaptation of the cerebellar–vestibular nuclei circuits, which could modulate the VOR gain through EH neurons. On the other hand, PVP neurons (type 1 PVP neurons more specifically) represent the majority of the intermediate neurons in the VOR pathway (Cullen 2016). These PVP neurons have been shown to present a reduced sensitivity to head velocity during VOR suppression (Cullen and McCrea 1993). Roy and Cullen (1998) went further and recorded neurons within the VOR pathways during eye-head gaze shift. Their results suggest that the modulation observed in PVP neurons originate from the burst neurons of the paramedian pontine reticular formation, which project inhibitory input to type I PVP neurons. This could suggest that VOR modulation could also originate from the brainstem structures. Secondly, other studies suggest a different mechanism to explain VOR gain modulation. Indeed, a study by Boyle et al. (2009) suggests that vestibular efferent pathways modulate peripheral neural signals. In their study, the authors electrically stimulated the Oyster toadfish's efferent vestibular system at the level of the brainstem and measured an inhibitory postsynaptic potential at the hair cell level, occurring 90 ms following electric stimulation of the efferent vestibular system. This latency is similar to that of VOR suppression in humans (Crane and Demers 1999; Cullen et al. 1991), which seems to support the hypothesis that efferent vestibular pathways could be involved in the suppression of the VOR. In line with the hypothesis of a modulation originating from the efferent vestibular system, Fitzpatrick and Watson (2015) looked at the effects of ambient motion exposition in normal healthy participants using galvanic vestibular stimulation on vestibular reflexes and perceptual response. After 10 min of vestibular stimulation, reflex amplitude was reduced and perceptual thresholds were increased. Fitzpatrick and Watson (2015) attributed these results to the modulation of vestibular afferent sensitivity through vestibular efferent pathways. However, this last hypothesis, involving a possible modulation of the vestibular primary afferents through the vestibular efferent system is in contradiction to many studies in monkeys, which suggests that the vestibular afferent signal is not modulated during head-on-body tasks (Cullen and Minor 2002; Sadeghi et al. 2007).

Overall, the present results confirm and add to those of previous studies in showing that VOR suppression is not a hard-wired reflex and that it can be modulated through training. Even if this design does not provide specific information about one type of dance, it adds to the ecological validity of the results. This finding could eventually make it possible to determine whether dance training could modulate VOR in patients with vestibular lesions, allowing to reduce their dizziness. Further studies are needed to shed light on the possible mechanism involved in this modulation of the VOR gain, but the observed changes in the vestibulo-cerebellum in dancers and its role in the modulation of the VOR gain makes the cerebellar–vestibular nuclei pathway a possible model to explain the results of the present study. Finally, further studies could investigate the possible influence of specific dance training on VOR suppression abilities.

Author contribution statement MM, LB and FC designed and performed the experiment. MM and FC wrote the paper and LB, AD, MN helped with the edition of the manuscript. All authors discussed the results and implications and commented on the manuscript at all stages.

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