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Repeated exposure to virtual reality decreases reliance on visual inputs for balance control in healthy adults

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ABSTRACT

Postural control may encounter acute challenges when individuals are immersed in a virtual reality (VR) environment, making VR a potential pertinent tool for enhancing balance capacity. Nonetheless, the effects of repeated exposure to VR on balance control remain to be fully elucidated. Fifty-five healthy participants stood upright for six bouts of 90 s each in an immersive virtual reality (VR) environment using a head-mounted display (repeated VR exposure). During these bouts, participants experienced simulated forward and backward displacements. Before and after the repeated VR exposure, the center of pressure mean velocity (VEL_{COP}) was measured in response to simulated forward and backward displacement in VR, as well as during quiet upright standing with eyes open (EO) and closed (EC) in the real environment. The results revealed a significant decrease in VEL_{COP} for forward and backward simulated displacements in both antero-posterior and medio-lateral directions ($p < 0.01$) after compared to before repeated VR exposure. Furthermore, VEL_{COP} significantly decreased when participants stood upright in EC (−5%; $p = 0.004$), but not EO (+3%; $p > 0.05$) in the real environment after repeated VR exposure. The Romberg ratio (EC/EO) was reduced in both antero-posterior and medio-lateral directions ($p < 0.05$) after VR exposure. This study indicates that repeated exposure to VR induces changes in balance control in both virtual and real environments. These changes may be attributed, in part, to a reduction in the weighting of visual inputs in the multisensory integration process occurring during upright standing. Accordingly, these findings highlight VR as a potentially effective tool for balance rehabilitation.

Significance statement: This study indicates that repeated exposure to VR induces changes in balance control in both virtual and real environments that can rely, in part, on a reduction in the weighting of visual inputs in the multisensory integration process occurring during upright standing.

1. Introduction

Balance control in upright standing relies on the integration of sensory information, primarily provided by the visual, vestibular, and proprioceptive systems (Peterka, 2002). An important focus in this area is to assess how sensory integration is processed and varies with balance conditions. Different theories and models explain the mechanisms by which the central nervous system (CNS) manages

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multisensory information (Maurer, Mergner, & Peterka, 2006; Peterka, 2002). It is assumed that during upright standing, information carried by individual sensory channels is combined, and a weight is assigned to the various inputs depending on the current functional state of the corresponding sensory system, the characteristics of the postural task, and the context in which the task is performed. During this process, the inputs from the most relevant sensory system are given more emphasis (up-weighted by the CNS), and inputs from the less reliable sensory system are given less emphasis (down-weighted by the CNS). In other words, postural control relies on multisensory integration, which does not appear to be merely an algebraic summation of individual cues but rather a weighted combination process; the weight given to each cue would be directly proportional to the relative reliability of the cue (Kabbaligere, Lee, & Layne, 2017).

Postural control can be investigated by recording the center of pressure (CoP), which reflects the trajectory of the center of mass and the amount of torque applied to the support surface to control its acceleration. However, the spontaneous sway measures from a force platform do not contain sufficient information to distinguish internal control dynamics (van der Kooij, van Asseldonk, & van der Helm, 2005). Therefore, CoP analysis, per se, does not allow the study of sensory reweighting, and specific experimental approaches are required. To this end, virtual reality (VR) can be a relevant tool as it allows participants to be totally immersed in a dynamic virtual environment that can generate postural adjustments (Chiarovano et al., 2017; Luo et al., 2018) and autonomic nervous system responses similar to those observed in real-life situations (Grosprêtre, Eon, & Marcel-Millet, 2023). In addition to its scientific relevance, these characteristics suggest VR as a potential clinical tool to restore balance capacitities. Interestingly, Fransson et al. (Fransson et al., 2019) showed a decrease in postural imbalance during repetitive exposures to a rollercoaster in VR, suggesting adaptations in balance control. However, a rollercoaster can be a very strong stimulus, which can induce cybersickness in some individuals, thereby limiting its use in clinical settings. It could therefore be interesting to know if a similar effect can be obtained with a less provocative stimulus.

Furthermore, to be clinically relevant, changes in balance control in response to VR exposure should be observed in a real environment. Akizuki et al. (Akizuki et al., 2005) reported a decrease in the Romberg ratio after repeated VR exposure consisting of a time lag between head movement and visual scene. The Romberg ratio, by comparing postural sway in eyes open (EO) and eyes closed (EC) conditions (EC/EO), quantifies the degree to which balance worsens when vision is removed compared to an eyes-open baseline, indirectly assessing the reliance to visual inputs in balance control (Howcroft, Lemaire, Kofman, & McIlroy, 2017; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996; Yang & Liu, 2020). The results from Akizuki et al. therefore suggest a reduced dependence on visual cues following virtual reality (VR) exposure. This finding is significant for individuals, especially older adults, who heavily rely on visual information to control upright standing, potentially increasing the risk of falls (Henry & Baudry, 2019). However, (Akiduki et al., 2003) reported an increase in body sway area both when individuals stood with eyes open or closed immediately after VR immersion. If such divergent results can arise from different experimental approaches, they do not answer the question of whether VR exposure can reduce visual reliance in a real environment.

Therefore, the present study aims to investigate the effects of repeated bouts of virtual alternated forward and backward displacements on balance control in virtual and real environments. Based on previous work (Akizuki et al., 2005; Fransson et al., 2019), a decrease in postural imbalance in the VR environment, as well as a decrease in CoP displacements during upright standing with eyes closed, are hypothesized.

2. Material and methods

2.1. Sample

Fifty-five adults [mean (SD); age: 31 (13) years; 29 women] volunteered to take part in this study after giving their written informed consent. Participants were enrolled in the study if they do not have neurological disorders with potential residual motor deficits (stroke, Parkinson's disease, multiple sclerosis, etc), diabetes, epilepsy, cardiac history, orthopaedic issues involving the lower limbs, and did not take medications that could influence balance (sedatives, hypnotics, antidepressants, and benzodiazepines). Approval for the project was obtained from the local Ethics Committee, and all procedures used in this study conformed to the Declaration of Helsinki.

2.2. Force platform

Participants were requested to stand on a force platform (OR6-6-2000, Advanced Mechanical Technology, Watertown, MA, USA). The signals from the platform were sampled at 25 Hz, A/D converted (Power 1401, 16-bit resolution, Cambridge Electronic Design, UK) and stored on a computer to compute off-line the position of the centre of pressure (CoP).

2.3. Virtual reality

The "Optic Flow" programme, included in the "Balance VR pack" developed by Virtualis (website: virtualisvr.com) was used, which consists of placing the participant in a virtual environment representing a tunnel with floating rocks. Linear forward displacement stimulus was provided by a centrifugal optic flow while linear backward displacement stimulus was provided by centripetal optic flow. Both direction of displacement was performed with a speed of 8 m/s. The acceleration and deceleration phases lasted 2 s. The virtual environment was displayed through a headset Vivo-Pro, which is equipped with G-sensor (2880 × 2800 combined pixels; 1440 × 1600 per eye; AMOLED).

2.4. Experimental protocol

The overall protocol comprised an acute intervention involving six bouts of simulated forward-backward displacement in the VR environment (repeated VR exposure). Before (pre-test) and after (post-test) the repeated VR exposure, assessments were conducted for postural response to optic flow in VR environment and balance performance in EO and EC conditions in a real environment. A schematic illustration of the protocol is presented in Fig. 1. In all experimental conditions, participants were instructed to stand in a bipedal position with a 10-cm distance between their heels and the forefeet oriented laterally with a 30-degree angle between them (each foot rotated 15° from the forward direction). Participants kept their arms at their sides and were instructed to refrain from any head or limb movements.

Pre-test: Participants were instructed to maintain upright standing as steadily as possible with EO and EC for 60 s each. A single trial for each visual condition was performed in a random order across participants, with a minimum of 30 s of rest between trials. While the standard practice involves three trials to assess postural sway in EO and EC conditions (Baudry & Duchateau, 2012, 2020), we opted for a single trial for each condition to prevent potential effects of repeated VR exposure from dissipating by the time of measurement. Pilot work in our laboratory ($n = 22$; unpublished data) demonstrated no significant difference between the mean value of a set of three trials and the value of the first trial of the set (Wilcoxon signed-rank test, $p > 0.05$), with interclass coefficient correlation of 0.93 and 0.95 for EO and EC, respectively.

Participants were then immersed in a virtual reality environment for two 60-s trials (with a minimum of 30 s of rest between trials), one simulating forward displacement and one simulating backward displacement (Fig. 2). The order of the two trials was randomly determined across participants. Each trial was divided into three epochs: the first 15 s involved no simulated displacement (No-DISP), the next 15 s featured simulated forward or backward displacement (DISP), and the final 30 s had no simulated displacement, allowing participants to restore balance.

Repeated VR exposure: Subsequently, participants underwent six bouts of 90 s in the VR environment. Each bout alternated between forward and backward displacements, with the number of shifts in direction being either 3 or 5. The duration of maintaining a direction of displacement was either 15 or 30 s (Fig. 1). The same six bouts were used for all participants but in a randomized order across participants.

Post-test: After the repeated VR exposure, participants underwent the same assessments as in the pre-test.

During pre- and post-tests, the trials without VR were always performed before the trials with VR, but the order of EO and EC, and forward and backward simulated displacement were counterbalanced across participants. However, for the same participant, the order of the different trials was the same for the pre- and post-tests.

To consider possible confounding factors to explain changes in postural control after repeated VR exposure, a pilot experiment was performed in 20 participants who underwent similar pre- and post-tests that those described above but without being submitted to the simulated displacement during repeated VR exposure. During the six 90-s bouts, the participants were placed in the same virtual environment that the one use for the repeated VR exposure (a tunnel with floating rocks) but no displacement was simulated. The participants were asked to do not move during the duration of the bout. None of the dependent variables changed over time (Wilcoxon signed-rank test), indicating that repeated VR exposure without simulated displacement did not induce any change in postural control.

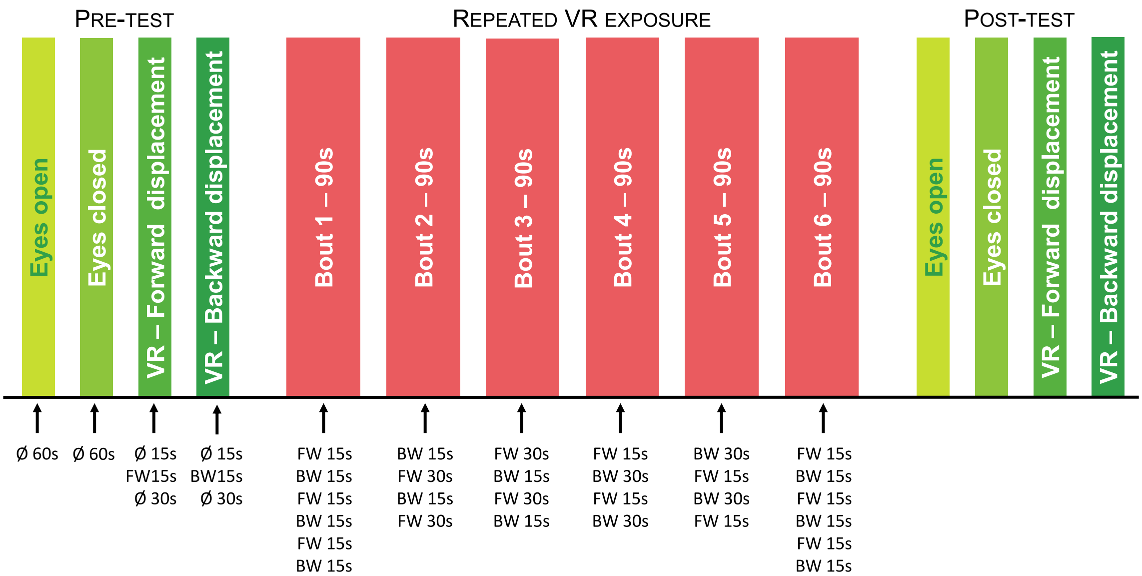

Fig. 1. Schematic representation of the protocol with the pre- and post-tests, and the repeated virtual reality (VR) exposure consisting of 6 bouts of 90s during which forward (FW) and backward (BW) simulated displacements were alternated. Each direction lasted either 15 or 30 s. ø indicates no simulated displacement. The eyes open and closed bouts were performed without the head-mounted display. During the pre- and post-test, the assessment of postural response to VR was performed with only one direction (FW or BW) in the same bout.

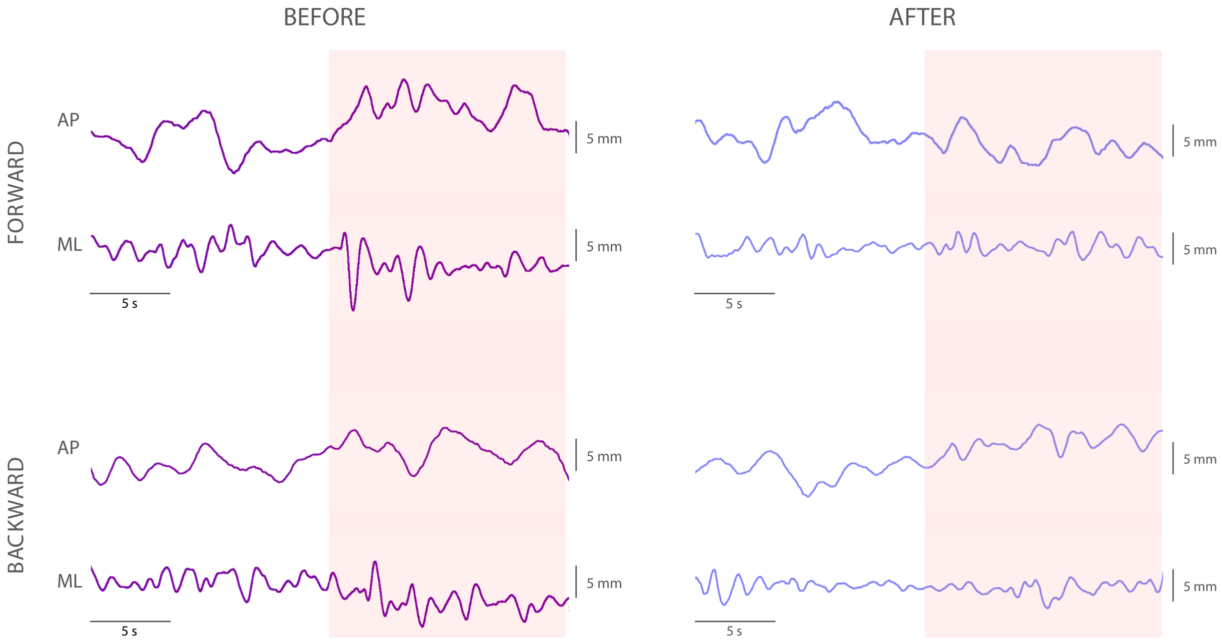

Fig. 2. Original traces of the center of pressure in antero-posterior direction (AP) and medio-lateral direction (ML) for one participant before (left column) and after (right column) the repeated virtual reality exposure during the first 30 s of the 60-s trials during which a simulated forward (first raw) and backward (second raw) was displayed during 15 s after an epoch of 15 s during which no displacement was simulated. The shaded zones represent the epoch during which the simulated displacement was displayed.

The full results of this pilot experiment are available in a supplemental file.

2.5. Data reduction

The displacement of the CoP was analyzed offline using Spike2 software (Cambridge Electronic Design, UK). Command lines were specifically written to process platform signals into CoP parameters. Initially, force platform signals underwent low-pass filtering (cut-off frequency: 10 Hz) using a fourth-order Butterworth filter. Subsequently, from the filtered data, the mean velocity of the total CoP displacement was calculated. The mean velocity of the CoP was chosen as it is considered one of the most reliable posturography measures (Low, Walsh, & Arkesteijn, 2017) and has been demonstrated to be influenced by vision (EO vs. EC) (Prieto et al., 1996) and to be predictive of balance capacity (Howcroft et al., 2017).

During simulated displacements in VR, the CoP mean velocity was computed for each 15-s epoch (No-DISP and DISP) independently for the antero-posterior direction (VR-VEL$_{AP}$) and the medio-lateral direction (VR-VEL$_{ML}$), and with both directions pooled (VR-VEL$_{COP}$). The dissociation between AP and ML directions was used to provide specific information on the effect of DISP, which was oriented in the AP direction, with the assumption that changes in VR-VEL$_{COP}$ should mainly be due to changes in VR-VEL$_{AP.}$ Accordingly, VR-VEL$_{ML}$ was also investigated to reinforce this rationale. To further assess the effect of the repeated VR exposure on the response to simulated displacement, the VR-VEL values measured during the simulated displacement (DISP) were expressed as a percentage relative to the values observed in the preceding 15 s (No-DISP).

In EO and EC conditions, the mean velocity of the CoP was calculated for a 40-s epoch, with the first 10 s discarded to avoid the stabilization process. This calculation was performed independently for the antero-posterior direction (VEL$_{AP}$) and the medio-lateral direction (VEL$_{ML}$), and with both directions pooled VEL$_{COP}$. The Romberg ratio was also calculated as the ratio between the CoP velocity variables recorded in EO and EC conditions (EC/EO).

2.6. Statistical analysis

A Shapiro-Wilk test was performed on each data set to assess their Gaussian distribution. As the distribution of the data was not distributed following a Gaussian function, the effect of repeated VR exposure (pre-test vs. post-test) was assess for each variable with a Wilcoxon signed-rank test. In addition, CoP velocity during the No-DISPL and DISPL conditions were compared in pre-tests with Wilcoxon signed-rank test to confirm that the virtual displacement induced a postural response. The level of significance was set at $p < 0.05$. Data are expressed as median (interquartile range) in the text and tables.

3. Results

3.1. Postural response to simulated displacement

At baseline, VR-VEL_{COP} increased from 6.8 (2.0) mm/s during No-DISP to 9.0 (4.1) mm/s during DISP condition for forward simulated displacement ($p < 0.001$) (Table 1). VR-VEL_{AP} and VR-VEL_{ML} were also greater during DISP than No-DISP ($p < 0.001$) (Fig. 3).

Similarly, all the VR-VEL parameters were greater for DISP compared with No-DISP during backward displacement ($p < 0.001$; Table 1).

After the repeated VR exposure, there was no change in No-DISP condition compared with before repeated VR exposure. In contrast, VR-VEL_{COP}, VR-VEL_{AP} and VR-VEL_{ML} were significantly lesser in DISP for both forward and backward displacement after compared with before repeated VR exposure ($p < 0.001$; Table 1). When expressing VR-VEL parameters during DISP relative to No-DISP to provide the extent of the postural perturbation in response to the simulated displacement, Fig. 3 shows that VR-VEL_{COP} [PRE: 130.1 (43.3)%; POST: 115.8 (22.7)%], VR-VEL_{AP} [PRE: 125.0 (44.1)%; POST: 119.2 (32.7)%] and VR-VEL_{ML} [PRE: 130.0 (48.7)%; POST: 113.4 (30.1)%] during simulated forward displacement were significantly lesser ($p < 0.01$) after compared to before repeated VR exposure. Similarly, during simulated backward displacement, VR-VEL_{COP} [PRE: 139.4 (55.1)%; POST: 113.4 (28.6)%], VR-VEL_{AP} [PRE: 136.6 (45.1)%; POST: 113.0 (29.1)%] and VR-VEL_{ML} [PRE: 147.6 (62.3)%; POST: 110.4 (34.9)%] were significantly lesser ($p < 0.01$) after than before repeated VR exposure.

3.2. Balance during eyes open and eyes closed conditions

There was no significant change in VEL_{COP}, VEL_{AP} and VEL_{ML} after the repeated VR exposure when standing with eyes open ($p > 0.05$; Table 2). In contrast, VEL_{COP} and VEL_{ML} decreased significantly ($p < 0.05$) after repeated VR exposure when standing with eyes closed.

The Romberg ratio decreased significantly for VEL_{COP} ($p < 0.006$), VEL_{AP} ($p < 0.004$) and VEL_{ML} ($p = 0.026$) after the repeated VR exposure (Fig. 4).

4. Discussion

This study explores the potential of repeated exposures to VR, simulating forward and backward displacements, to induce changes in controlling balance during upright standing. To this end, postural responses to simulated displacement and postural control in real environments were investigated. The data reveal a diminished postural response to simulated displacement and increased stability when standing with eyes closed, accompanied by a decrease in the Romberg ratio. These findings suggest that repeated exposure to VR, simulating forward and backward displacement, could transiently reduce the reliance of balance control on visual inputs.

4.1. Simulated forward and backward simulated displacement evoked postural reponse

The motion of the visual surround has long been recognized to induce postural reactions in humans, as shown by Lee and Aronson by using an experimental moving room that could move forward and backward (Lee & Aronson, 1974). A recent research reported similar postural effects using a virtual "moving room" (Chander et al., 2019). Similarly, the forward or backward movement of the visual scene in VR environment induced postural responses in young, healthy adults (Heidner et al., 2020; Phillips, dos Santos, & Santoso, 2022).

Consistent with these prior studies on healthy adults, the simulated displacements employed in the current study elicited postural responses in both forward and backward directions. As participants had no cues to anticipate the onset of the simulated displacement, the postural response to simulated displacement is expected to reflect a reactive reaction to the initial illusion of displacement (Guerraz, Thilo, Bronstein, & Gresty, 2001). This is likely followed by the postural effect of suppressing visual information in favor of

Table 1
Mean centre of pressure velocity in both antero-posterior and medio-lateral directions (VEL_{COP}), in anterio-posterior direction only (VEL_{AP}) and medio-lateral direction only (VEL_{ML}) during the 15 s in virtual reality (VR) environment without (No-DISPL) and with (DISP) the simulated forward or backward displacement, before (PRE) and after (POST) the repeated VR exposure.

	FORWARD		BACKWARD	
	PRE	POST	PRE	POST
VR-VEL_{COP} (mm/s) – *No-DISPL*	6.8 (2.0)	7.1 (1.5)	7.1 (1.6)	6.9 (1.7)
VR-VEL_{COP} (mm/s) – *DISP*	9.0 (4.1)	8.1 (2.1)***	10.4 (4.5)	7.8 (2.2)***
VR-VEL_{AP} (mm/s) – *No-DISP*	4.1 (1.3)	4.2 (0.9)	4.3 (0.9)	4.2 (1.1)
VR-VEL_{AP} (mm/s) – *DISP*	5.2 (1.8)	4.7 (1.6)**	5.8 (2.1)	4.7 (1.3)***
VR-VEL_{ML} (mm/s) – *No-DISP*	4.7 (1.7)	4.8 (1.5)	4.8 (1.1)	4.5 (1.7)
VR-VEL_{ML} (mm/s) – *No-DISP*	6.5 (3.4)	5.3 (1.8)***	6.8 3.8)	5.3 (1.7)***

** and *** denotes a significant difference with PRE at $p < 0.01$ and $p < 0.001$, respectively. Values are expressed as median (interquartile range).

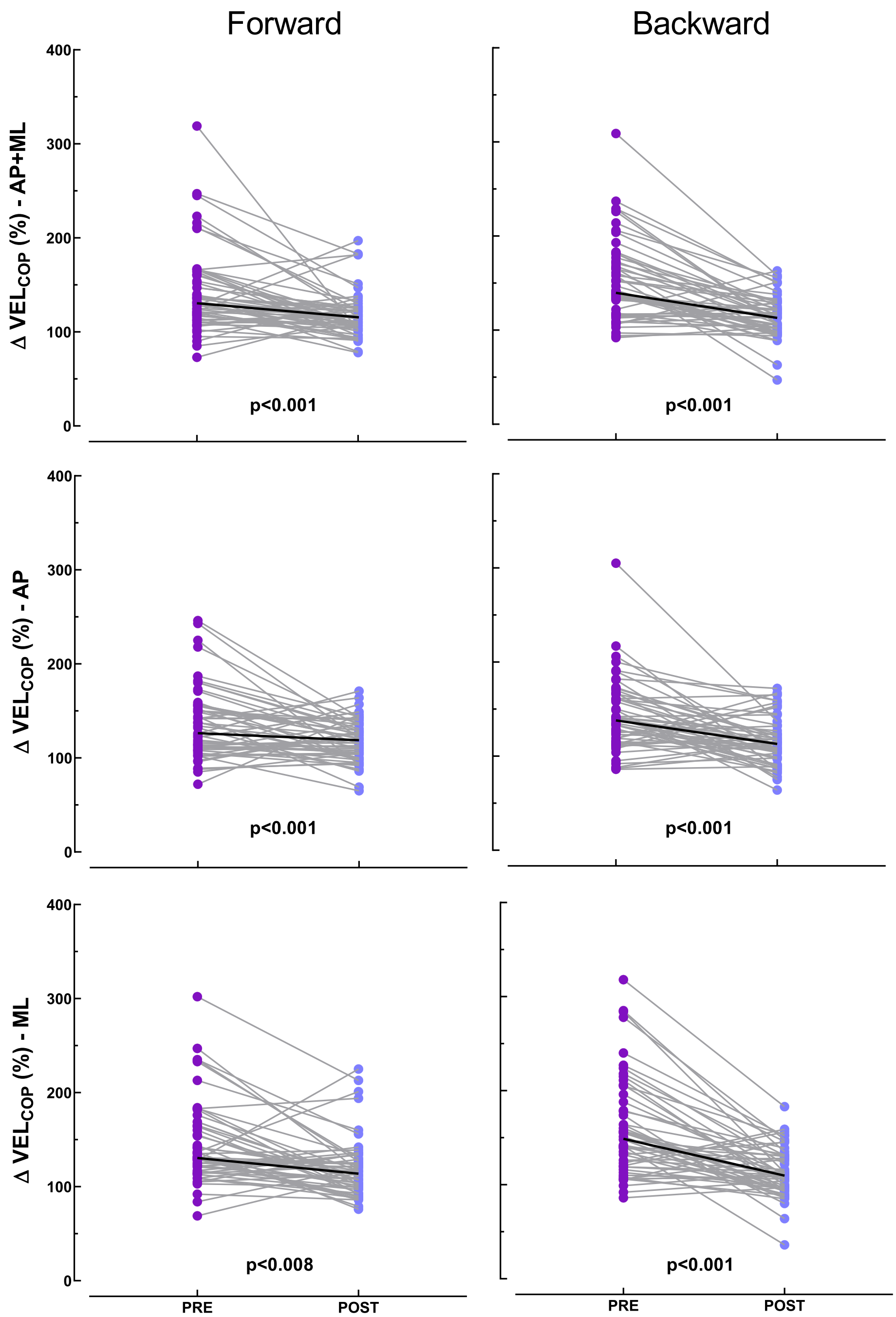

Fig. 3. Effect of the simulated displacement (forward: left column; backward: right column), expressed as percent of the baseline, on the mean centre of pressure velocity (VEL_{COP}) in both antero-posterior and medio-lateral directions (AP + ML), in anterio-posterior direction only (AP) and medio-lateral direction only (ML) before (PRE) and after (POST) the repeated virtual reality exposure. The *p* values denote significant differences between PRE and POST. Each point represents individual data, and the thick black line links the median values from PRE to POST.

proprioceptive and vestibular information to compensate for the initial visual perturbation (Bronstein, 1986; Lee & Aronson, 1974; Pletcher et al., 2017).

The present results indicate that forward and backward simulated displacements not only evoked postural response in AP direction but also in ML direction (Fig. 3). Such lateral responses to forward-backward optic flow have already been observed (Raffi, Piras, Persiani, & Squatrito, 2014; Raffi, Trofè, Meoni, & Piras, 2022). In these studies, the authors highlighted these lateral responses can arise from differences in the role each leg played in the control of stance, with a possible sex effect. In the current study, our objective was not to analyse the laterality of the balance control, using thereby only one force platform. It is therefore difficult to discuss the

Table 2
Mean centre of pressure velocity in both antero-posterior and medio-lateral directions (VEL_{COP}), in anterio-posterior direction only (VEL_{AP}) and medio-lateral direction only (VEL_{ML}) before (PRE) and after (POST) the repeated VR exposure.

	Eyes Open		Eyes closed	
	PRE	POST	PRE	POST
VEL_{COP} (mm/s)	7.6 (1.7)	7.3 (1.5)	8.2 (2.0)	8.0 (1.6)*
VEL_{AP} (mm/s)	4.1 (0.7)	4.1 (0.7)	4.9 (0.8)	4.8 (0.9)
VEL_{ML} (mm/s)	5.2 (1.4)	4.9 (1.6)	5.5 (1.6)	5.3 (1.5)*

* Denotes a significant difference ($p < 0.05$) with PRE. Values are expressed as median (interquartile range).

present results more deeply. Nonetheless, our results suggest that the postural response may not be solely dependent on the direction of the simulated translational displacement although these results should be confirmed through further investigations utilizing right and left simulated displacement.

4.2. Decrease in postural response to virtual displacement after repeated VR exposure

Fransson et al. previously reported an adaptation to repeated simulations of a rollercoaster motion, demonstrating a reduced postural instability across five repeated simulations (90 s each; Fransson et al., 2019). The current findings corroborate that repeated exposure to VR can induce postural adaptations, resulting in decreased postural instability. Notably, the enhanced stability observed in the present study after repeated VR exposure was significant for both antero-posterior and medio-lateral directions. This suggests that the central nervous system (CNS) undergoes adaptations in multiple directions, even though the biomechanical constraints differ between these directions (antero-posterior and medio-lateral).

The decreased postural response to simulated forward and backward displacement might indicate a habituation process to the visual stimulus. Habituation involves a progressive decrease in the amplitude or frequency of a motor response to repeated sensory stimulation, not caused by sensor adaptation (Schmid, Wilson, & Rankin, 2015). Habituation could stem from a decreased sensitivity to stimuli (Schmuckler, 1997) or a learning effect optimizing the response strategy (Duncan, Langlois, Albert, & MacKinnon, 2014). Previous research reported a decrease in the magnitude of the postural response to repeated mechanical perturbations, with a greater response during the first trial compared to the second and third trials (Duncan et al., 2014; Nanhoe-Mahabier et al., 2012). Similarly, Schmuckler (Schmuckler, 1997) suggested possible habituation to oscillations of the surround, leading to a decrease in postural response in the absence of sensory reweighting.

However, several lines of evidence indicate a potential role of sensory reweighting. Firstly, theories and models (Maurer et al., 2006; Peterka, 2002), supported by experimental data (Assländer et al., 2023; Baudry & Duchateau, 2012, 2020; Kabbaligere, Lee and Layne, 2017; Pletcher et al., 2017), emphasize that information carried by individual sensory channels is combined, and a weight is assigned to various sensory inputs based on the current functional state of a particular sensory channel. Consequently, repeated exposure to a similar postural threat induced by an optic flow should lead to the down-weighting of less reliable sensory inputs (visual information) and up-weighting of more reliable ones (proprioceptive and vestibular information). Secondly, as participants stood on a stable and firm surface (force platform), the stationary cues provided by the mechanoreceptors (sensors specialized in mechano-transduction) of the proprioceptive system are likely processed as being more reliable. It is well-known that both muscle (Baudry & Duchateau, 2020; Eklund, 1972; Henry & Baudry, 2019; Roll, Vedel, & Ribot, 1989) and skin sensors (Macefield, 2021; Modig, Patel, Magnusson, & Fransson, 2012; Viseux et al., 2019) play a key role in postural control. The exquisite inputs from these sensors likely contribute to a shift from self-motion sensation to visual motion, supporting a sensory reweighting characterized by the down-weighting of visual information and likely an up-weighting of proprioceptive inputs, although vestibular inputs can also be up-weighted (Akiduki et al., 2003). Thirdly, the decrease in CoP velocity during upright standing with eyes closed after repeated VR exposure (see below) cannot be explained by a habituation process.

In summary, the present results suggest that repeated VR exposure reduce postural instability during provocative simulations of forward and backward displacements. This reduction can be explained by a habituation process and/or a sensory reweighting decreasing the reliance to visual inputs for balance control.

4.3. Decreased in romberg ratio after repeated VR exposure

After repeated VR exposure, there was no change in the mean CoP velocity when participants stood with eyes open, indicating that postural control in this visual condition remained unaffected by the repeated VR exposure, in line with previous research (Akizuki et al., 2005). In contrast, postural stability improved when standing with eyes closed, suggesting that repeated VR exposure could influence postural control when visual information was occluded. Additionally, the Romberg ratio decreased after repeated VR exposure. Akizuki et al. (Akizuki et al., 2005) reported a similar decrease in the Romberg ratio in their study, primarily attributed to a non-significant reduction in body sway when participants stood with eyes closed. In the present study, both a significant decrease in mean CoP velocity when standing with eyes closed and a decrease in the Romberg ratio were observed. The slight discrepancies between the studies could stem from methodological differences. Akizuki et al. did not simulate displacement but introduced a time lag between head movement and the visual scene. In contrast, our study used a more provocative stimulus that may intensify the need for postural adaptation. Furthermore, the present results were obtained from 55 participants, thereby increasing the statistical power,

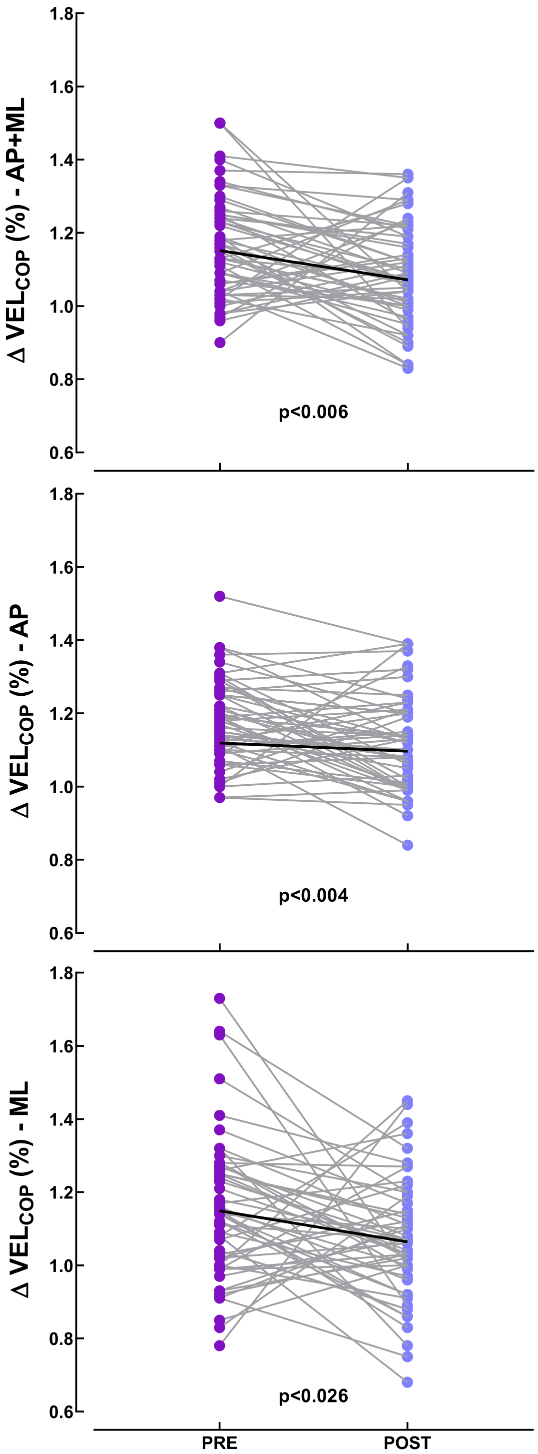

Fig. 4. Romberg ratio (eyes closed/eyes open values) computed from the mean centre of pressure velocity in both antero-posterior and medio-lateral directions (AP + ML), in anterio-posterior direction only (AP) and medio-lateral direction only (ML) before (PRE) and after (POST) the repeated virtual reality exposure. The p values denote significant differences between PRE and POST. Each point represents individual data, and the thick black line links the median values from PRE to POST.

compared to the study by Akizuki et al. ($n = 23$). This observation, coupled with the visual inspection of the data presented in Figs. 2 and 3, emphasizes the variability in the effects of repeated virtual reality (VR) exposure. Such variability may stem from factors like an insufficient number of bouts or the presence of responders and non-responders to this type of stimulus.

As the Romberg ratio assesses the extent to which balance deteriorates when vision is removed compared to an eyes-open baseline (Howcroft et al., 2017), both studies suggest a decreased reliance on visual cues during upright standing after repeated VR exposure, even in the absence of a visual threat. Unlike the decrease in postural response in VR, the results on the Romberg ratio cannot be attributed to a habituation process, as no stimulus or perturbation was present during the trial. It may be hypothesized that sensory reweighting occurs during repeated VR exposure, with a possible continuous expression of it during upright standing in a real environment. This suggests that repeated VR exposure can transiently alter how the central nervous system controls balance in upright standing, by reducing the dependency on visual information.

4.4. Practical implications

The present study offers valuable insights into the impact of repeated VR exposure on postural control. Firstly, the suggested decrease in reliance on visual input holds potential significance for populations characterized by increased visual dependency in postural control, such as older adults facing alterations in proprioceptive sensors and signal integration, potentially elevating the risk of falls (Henry & Baudry, 2019). Moreover, it is noteworthy that improvements in balance stability were observed in both antero-posterior and medio-lateral directions, with medio-lateral stability shown to be linked to a higher risk of falls (Audiffren, Bargiotas, Vayatis, Vidal, & Ricard, 2016; Bauer, Gröger, Rupprecht, Marcar, & Gaßmann, 2016; Piirtola & Era, 2006). Consequently, the potential to diminish visual dependency in postural control and enhance medio-lateral balance through VR could be particularly beneficial for older adults. This is especially pertinent given that the VR stimulation employed in the present study did not induce cybersickness, suggesting its appropriateness for balance training.

4.5. Methodological considerations

One of the primary strengths of this study lies in its substantial sample size ($n = 55$) and the experimental approach, demonstrating that repeated VR exposure can induce changes in postural control in both VR and real environments. However, several considerations should be considered. Firstly, the participants' average age was 31 years, which may limit the generalizability of the findings to other populations. Although the clinical implications of the current data are exciting, it is crucial to confirm whether repeated VR exposure also reduces visual dependency in older adults. Notably, Eikema and colleagues reported that older adults exhibit less sensory reweighting during quiet standing due to greater visual field dependence (Eikema, Hatzitaki, Tzovaras, & Papaxanthis, 2012). Further research is necessary to validate the present results in older adults. Secondly, the observed changes in postural control in this study are likely transient. However, the protocol used does not provide insights into the duration of this effect, and there is a lack of literature assessing any lasting effects of repeated VR exposure. Therefore, further investigation is warranted, especially when considering the potential chronic use of this intervention to achieve cumulative effects.

5. Conclusion

The present study demonstrates that six sessions of 90 s each involving provocative simulations of forward and backward displacement in VR environment induce changes in postural control. These changes are characterized by a reduction in postural instability in response to virtual displacement and a decrease in the Romberg ratio when participants stand in a real environment. Consequently, repeated VR exposure appears to diminish reliance on visual inputs for balance control. This suggests that VR could be a potentially effective tool for balance rehabilitation. However, further research is needed to confirm and explore the full extent of this potential.

CRediT authorship contribution statement

Christophe Barbanchon: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Dominique Mouraux:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Stéphane Baudry:** Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare no competing financial interests.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2024.103236.

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