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Original article

Modulating the internal model of verticality by virtual reality and body-weight support walking: A pilot study

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ABSTRACT

Background and objective: The study aimed at inducing a visual vertical (VV) bias by immersion in a virtual tilted room (VTR, visual cues), then testing the effect of 30% body-weight support walking (BWSW, somaesthetic cues) to correct this bias.
Methods: We included 20 healthy participants (median age 54 years; 12 females) who wore the Oculus-Rift® Head Mounted Display to produce the virtual reality and generate the VV. VV (8 trials) was tested at baseline, then in 3 postural conditions (walking, sitting and BWSW), by 2 visual conditions (darkness and VTR), according to a pseudo-randomized blocked design. The VTR was tilted 18° clockwise. Data for 3 participants with virtual reality sickness were discarded, and those for 17 participants underwent non-parametric statistical analysis by 2 main criteria: VV and head orientation.
Results: The VTR induced a pronounced tilt of the vertical toward the tilted side under the baseline condition (median 11.4° [Q1–Q3 6.1–13.4]; $P < 0.01$), with a large effect size ($r = 0.88$). The effect was systematic, with great inter-individual variability (2–17°), and was similar under every postural condition ($P < 0.001$), with a post-effect lasting 6 min and suppressed under BWSW. In darkness, VV was more upright during BWSW than sitting ($P < 0.05$), with a medium effect size ($r = 0.49$). The VTR induced a slight head tilt of median 3.3° [2.8–5.9] toward the tilted side under every postural condition ($P < 0.001$), with a large effect size ($r = 0.87$). In darkness, the head was upright only at baseline and under BWSW.
Conclusion: Being immersed in a tilted environment induces a powerful bias in verticality perception (11°). Contrary to our hypothesis, BWSW did not attenuate the effect induced by the VTR, probably because of the power of this effect. However, BWSW was the only postural condition able to suppress post-effects induced by the VTR, thereby leading to the head and VV oriented upright. BWSW may improve verticality representation, presumably by bringing augmented information about the direction of the Earth vertical. These findings represent an avenue for rehabilitation of patients with postural disorders caused by a wrong verticality representation. Technological improvements will be necessary to attenuate the virtual reality discomfort.

1. Introduction

Internal models serve sensory processing, sensory-motor integration and motor control [1]. They could be a way to construct and update the sense of verticality, by combining vestibular and somatosensory graviception and vision [1,2]. The accuracy of the sense of verticality allows for explicitly perceiving the direction of gravity, building a mental representation of this direction and using the resulting representation to orient the body with respect to gravity. A normal representation of the vertical is required to stand upright and thus walk normally. Some patients with a brain lesion show a bias in the internal model of verticality and consequently align their body with this wrong representation of the vertical, which causes lateropulsion or retropulsion, thereby altering gait. The development of rehabilitation techniques modulating the internal model of verticality is a major challenge

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for balance and gait disorders related to a misorientation with respect to gravity.

Manipulating static [3,4] or dynamic [5,6] vision is long known to have a powerful effect on perception of the vertical. As galvanic vestibular [7,8] or somaesthetic stimulations [2,9–13], dynamic visual stimulations [5,6] interact with balance control. Static visual manipulation has the advantage of strongly modulating the internal model of verticality without interfering with postural stabilization [14]. A static tilt of the environment attracts the visual vertical (VV) to the side with maximal effect for a frame tilted 15 to 20° away from the vertical [14,15]. The effect is stronger with cognitive and structural 3D enrichment [15,16] or by immersion in a real tilted environment [4,6,17], which is difficult to implement in a rehabilitation context. New technologies such as virtual reality allow for such complete immersion in a tilted virtual environment, with an effect on perception of the vertical, which remains to be tested.

The first hypothesis of this study was that immersion in a virtual tilted room (VTR) would induce a powerful bias in verticality perception, without preventing the performance of a dynamic task such as walking. Virtual reality is increasingly used in neurosciences, to understand mechanisms [18], quantify spatial deficits [19] and train patients, especially with postural and locomotor task after a stroke [20]. This tool has recently been proposed to assess the VV in static and dynamic conditions [21]. The present study was performed in line with these perspectives.

Post-stroke lateropulsion may be attenuated after body-weight support walking (BWSW) [12]. Our second hypothesis was that BWSW should modulate verticality representation because of the vertical tension yielded by the suspension cable, which gives the brain relevant feedback about the Earth vertical while performing a walking task on a treadmill.

The idea of this pilot study was to experimentally create a VV tilt by using a VTR, then examine how walking suspended or not might affect verticality representation.

2. Methods

2.1. Participants

All 20 healthy participants gave written informed consent and the study was performed in compliance with the Helsinki Declaration. Because of the novelty of the study, the sample size could not be calculated but was targeted at about 15 participants, which is usually sufficient for concluding on verticality perception in experimental studies with healthy controls [9,11] and should be adapted to prepare a further randomized clinical trial in patients. Inclusion criteria were age over 35 years, no neurological or vestibular history, no cognitive or psychiatric disorders and/or gait disturbance. We anticipated that some participants may meet exclusion criterion *a priori* defined as an orientation of the VV beyond usual normal ranges (i.e., ± 2.5° [22]), or might experience virtual reality sickness, so we recruited 20 healthy participants (staff members and relatives) naive to the hypotheses. Their characteristics (presented as median [Q1–Q3]) were age 54 [49–56] years, 12 females; body weight 69 [62–79] kg and height 1.70 [1.65–1.74] m. Their physical activity was classified as high (> 3 h/week, $n = 11$) or low (< 3 h/week, $n = 9$).

2.2. Study design

First, baseline VV was assessed in the sitting position, head and trunk free, after 2 min spent in darkness (head-mounted display [HMD] worn but off) (Fig. 1). VV was successively tested under a dark condition and in the VTR to record reference values for both visual conditions, without any possible interaction with a post-effect induced by a preceding condition/task. Then, VV was tested in 3 postural conditions (walking, sitting and BWSW) according to a pseudo-randomized blocked design (Fig. 1), crossing each postural task with 2 visual conditions (darkness first, then immersive VTR). To avoid any effects related to learning or fatigue, 10 participants were pseudo-randomly allocated to

Fig. 1. Protocol diagram, with visual vertical (VV) evaluations in red and postural tasks in blue. Participants were pseudo-randomized in 2 sequences, A or B, with postural tasks performed in reversed orders.

sequence A (walking/sitting/BWSW) and the 10 others with comparable characteristics to sequence B in a reverse order (BWSW/sitting/walking). The sitting task was systematically performed in the middle to serve as resting phase. Each postural task began with 2 min in immersion in an upright virtual bedroom (identical to the one used for the VTR), which allowed for better control of visual cueing and preventing possible dizziness feelings by walking too long in darkness. Then VV evaluation was launched and lasted about 3 min

The measurements recorded in the VTR condition aimed at analyzing how VTR could modulate verticality perception. The measurements recorded in the 3 postural conditions aimed at analyzing how a given postural task could modulate verticality perception. Apart from baseline, the measurements recorded in darkness served first as reference values for a given postural task and second to analyze the persistence of a post-effect secondary to the previous VTR. If present, a post-effect lasted at least 6 min, which corresponded to the time required to switch from one postural task to the next, the first 2 min during which the subject performed the task immersed in a virtual room oriented on the Earth vertical, then 3 min to perform the VV evaluation in darkness. Post-effects are rarely quantified in studies analyzing VV modulation and had never been evaluated with virtual room. This estimation was one of the secondary objectives of the present study. The whole experiment lasted about 45 min.

2.3. Experimental conditions

2.3.1. Visual surrounding

Throughout the whole procedure, participants wore the Oculus Rift DK2® HMD (Oculus, Menlo Park, CA, USA), which delivered the VV evaluation module generated by the software PosturoVR 0.8.3 (Virtualis, France). They used their usual glasses within the device to correct vision if needed.

We used two immersive static environments presented in Fig. 2:

- a dark-blue background without visual clues (called darkness);
- a VTR in which participants were totally immersed as if they stood in a 3D tilted cube containing typical bedroom objects.

The tilted orientation of the scene was stabilized on the Earth vertical regardless of head orientation owing to the gyrometer of the device. This sensor compensated for the head movements so that the orientation of the room stayed set on the Earth vertical or tilted 18° clockwise. This amplitude was found optimal to induce a VV modulation by tilting a visual frame in a dark surrounding, with less uncertainty with the clockwise direction [15]. Only the clockwise direction was chosen so as to simplify the protocol and for further studies with people with a right-hemisphere stroke. The virtual reality HMD was 1920 pixels wide × 1080 pixels high (960 × 1080 per eye) with a 100° field of view.

2.3.2. Postural tasks

Participants wore a harness during the protocol to perform the experiment safely and quickly and to avoid biasing data by wearing the harness only in the required condition BWSW. We used a commercialized harness (Biodex Company, Shirley, NY, USA) with 3 points of pressure (hip straps, gluteal fold straps and lumbar-thoracic harness) and 2 shoulder straps suspending each hemibody to the ends of a cross bar, itself hooked to the framework in a single-point suspension (video).

During sitting, participants were seated without a back support on a chair placed on the treadmill (immobile). Their hands were laid one over the other on their thighs, and their head and trunk were free. Contrary to the standard [22,23], we chose not to maintain the head in none of the 3 postural conditions because this was not possible for walking and also to monitor the head orientation. For the 2 walking conditions, participants walked on a RTM600™ treadmill device at a comfortable speed (3 km/h). In the suspended condition, 30% body weight was unloaded. The experiment was supervised by 2 people, one responsible for safety and remaining close to the treadmill and the other responsible for data acquisition. Because of the supposed difficulty of walking on a treadmill while being immersed in a VTR, all participants were asked to hold onto the handrails of the device under both walking conditions.

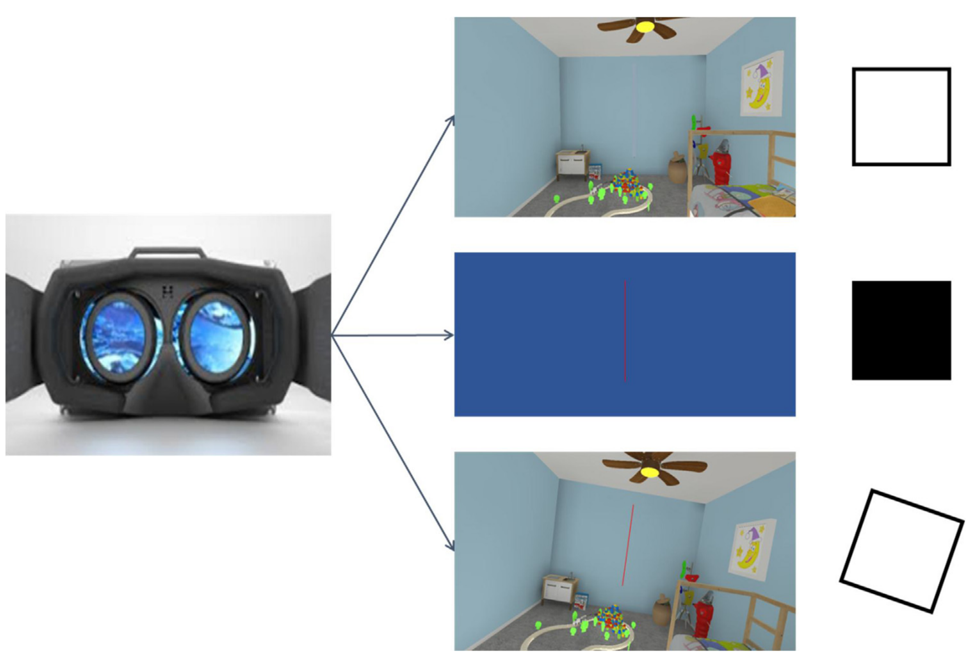

Fig. 2. Oculus Rift® head-mounted display and the 3 virtual environments delivered, in which participants were successively immersed.

2.4. Outcome criteria

To test VV, participants were asked to orient a red line vertically by giving oral instructions to the examiner. For each of the 8 trials of VV measurement blocks, the initial tilt of the line was randomly determined by the software (−80 to 80°), to avoid repeating the same sequences in an experiment consisting of numerous VV estimates per participant [22].

Before completing the protocol, participants were familiarized with the experimental set-up and performed 2 practice trials. The study involved no time constraints or performance feedback between measures. In the VTR condition, the visual line appeared to be displayed on the front wall 3 m away, giving 1.80 m length and 1-cm width for a 33° angular size in the visual field. The line had the same dimensions in darkness. VV was measured in terms of the Earth vertical with the gyrometer of the device. The 0.2° step-width gave the accuracy. VV orientation, calculated as the average of each block of 8 trials (2 blocks per postural conditions), was the primary outcome of the study. By convention, a positive value corresponded to a VV tilt oriented toward the VTR. VV uncertainty was the second criterion, calculated as the standard deviation for each block of 8 trials. Head orientation was the third criterion. Head orientation had to be controlled to analyze the possible effect of a VTR on head orientation in the 3 postural conditions, given the well-known effect of head orientation on VV [23,24], and since the head had to remain free not to interact with the BWSW. Hence, the mean head orientation during each block of VV was monitored by use of an on-board accelerometer and gyroscope combined in one sensor, a gyrometer, the accuracy of which was 0.01°. A positive value corresponded to a head tilt toward the VTR.

3. Statistical analysis

Statistical analyses were mainly conducted with SPSS v23 (IBM Corp., Armonk, NY, USA). Descriptive statistics were generated for all variables. We tested the normality of data distribution per associated variables (2 visual and 4 postural conditions for both VV orientation, uncertainty and head orientation) by the Shapiro–Wilk test. The normality assumption was not always met, so all statistical analyses were performed with non-parametric tests. VV orientation in darkness and VTR were compared by the Wilcoxon signed rank test, first at baseline and then in the 3 postural conditions. At baseline, we tested the effect of age, sex and physical activity on VV bias magnitude to search for an explanatory factor of inter-individual variability. To search for a post-effect, VV orientations in darkness were compared to 0 (Earth vertical orientation) by using the one-sample Wilcoxon signed rank test. Differences between postural conditions were tested by the Friedman test and when significant, followed by pairwise multiple comparisons according to Siegel & Castellan [25] by using Microsoft Excel (2010). Bilateral statistics were used, so the α risk was fixed at $P < 0.05$. Effect sizes were calculated by hand by using the Z values of the Mann–Whitney test $\left[r = \frac{Z}{\sqrt{N}}\right]$, as proposed by Tomczak & Tomczak (2014) for non-parametric statistics [26]. Effect sizes were interpreted according to Cohen's guidelines (1988): small, $r > 0.09$; medium, $r > 0.29$; and large, $r > 0.49$ [26,27]. Unless otherwise indicated, data are presented as median [Q1–Q3].

4. Results

4.1. Feasibility of the study

Among the 20 participants recruited, 2 had abnormal VV at baseline (3° and 3.8°), one also showing dizziness when wearing the device. A third participant experienced dizziness with nausea and complained of discomfort during the whole protocol, which was completed with difficulty. Both participants showing dizziness were asked to quantify their discomfort on a numerical scale (0 no discomfort; 10 maximal discomfort). The score was 6/10, which indicated a substantial level of discomfort precluding a reliable analysis of their spatial estimates. Because of these adverse effects, the experiment was considered not feasible in 3/20 participants (15%). As planned *a priori*, data for these 3 participants were discarded and analyses were conducted for the 17 other participants. Among participants who completed the experiment, 12/17 (70%) reported a discomfort, always experienced at the end of each VV evaluation sequence. This discomfort was slight and transitory and did not compromise continuing the experiment.

5. Normal values for VV tested head free with the Oculus Rift device

Baseline data are presented in Fig. 3. In sitting, VV was not significantly different from zero in darkness (median: 0.6° [−0.2 to 0.9], 95% confidence interval −0.3 to +0.7° $Z = -1.01$; $P = 0.33$). If we add a possible measurement error due to the accuracy of the device and to remain symmetrical with respect to zero, a first indication of the ranges of normality for VV tested with the Oculus Rift device would be −1° to +1°. During sitting in darkness, the uncertainty was 0.7° [0.5–0.8] (95% confidence interval +0.6 to +0.8°, which gave a threshold of 1° to define normality.

6. VV modulation

The VTR induced a pronounced tilt of the vertical toward the tilted side under the baseline condition (median 11.4° [6.1–13.4]; $Z = -3.62$; $P < 0.01$), with a large effect size ($r = 0.88$). Although the VTR effect was systematic (all subjects), we found great inter-individual variability, with an effect ranging from a few degrees to 16.9°. This variability was not explained by any of the participants' characteristics because the VV bias magnitude was not correlated with age, sex or physical activity level. Fig. 4 shows that the VTR effect was found in every postural condition ($P < 0.001$), with a magnitude similar to that found at baseline and without any effect of the task (sitting, walking or BWSW). Fig. 5 shows VV in darkness by postural condition. During sitting, VV did not differ much from the Earth vertical ($Z = -1.80$; $P = 0.076$), with a tilt to the side of the VTR used in the condition 6 min before (see experimental plan in Fig. 1). This finding suggests the existence of a post-effect, lasting for at least 6 min. For the walking conditions, VV was no longer different from the Earth vertical: walking without BWS ($Z = -1.18$; $P = 0.25$) and BWSW ($Z = -0.62$; $P = 0.55$). These findings indicate no post-effect under walking conditions. Moreover, in darkness, VV was different in the 3 postural conditions as compared with the Friedman test ($X^2(2) = 7.42$; $P = 0.02$). Post-hoc analysis with multiple comparisons showed that VV tilt was lower in the BWSW than the sitting condition ($Z = -2.01$; $P < 0.05$), with a medium effect size attributed to the BWSW ($r = 0.49$). Individual data displayed in Fig. 5A show that for 13/17 participants, the VV bias was lower in BWSW than sitting, with a median decrease of 0.7° for all participants. These findings indicate that the post-effect in sitting was suppressed when participants walked suspended (magnitude of VV tilt significantly divided by 2 and no longer different from the Earth vertical). Walking without being suspended was an intermediate condition, without a significant effect but an attenuated post-effect, with data not different from the Earth vertical.

The uncertainty of VV was also affected by the immersion in VTR. Under the baseline condition in sitting, the uncertainty was higher in VTR than in darkness (median 1.1° [0.8–1.6] vs 0.7° [0.5–0.8]; $Z = -2.43$; $P = 0.02$), with a large effect size ($r = 0.59$). This effect was

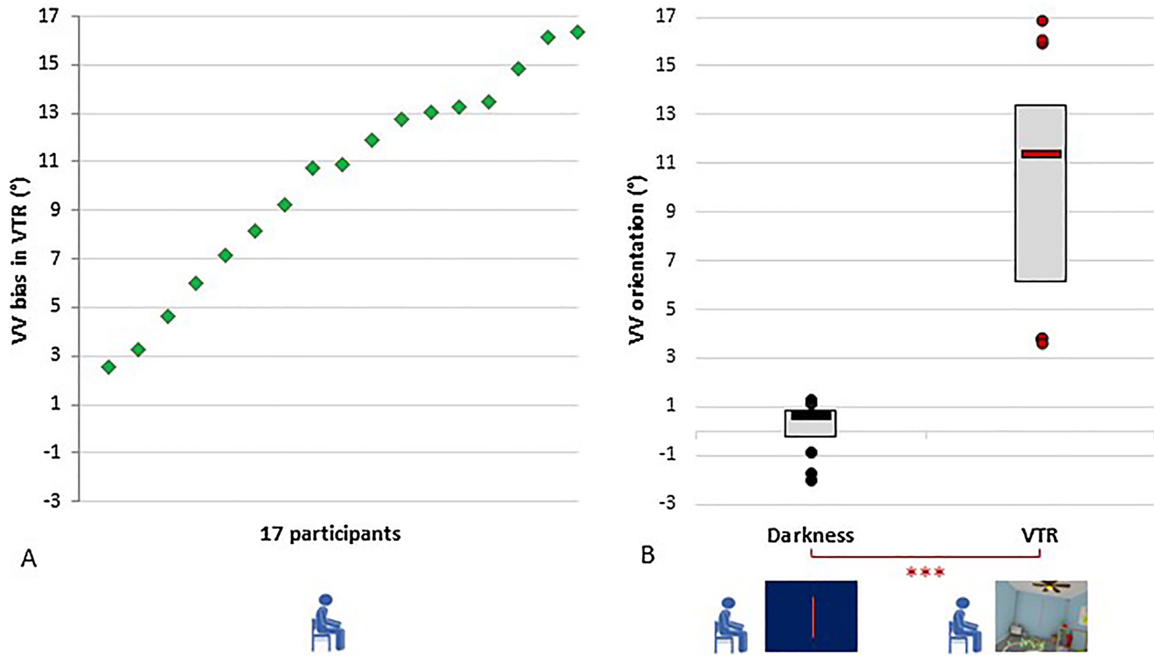

Fig. 3. A. Individual VV bias (difference between darkness and virtual tilted room [VTR) induced by the immersion in VTR for each of the 17 participants. All biases were positive, meaning clockwise tilt of the VV (same direction as the VTR). B. Box plot representation of VV orientation in darkness and in VTR, measured in baseline. Positive values indicate clockwise tilt of the VV (same direction as the VTR). Data are median (Q1–Q3). ***$P < 0.001$ for the difference between VTR and darkness.

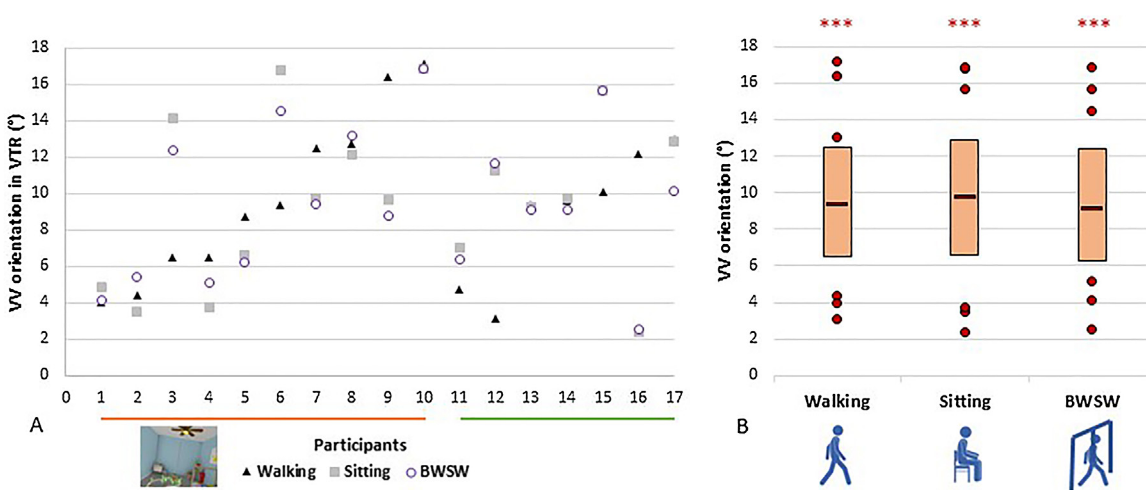

Fig. 4. A. Individual VV orientations in VTR for each postural condition (sitting, walking and body-weight support walking [BWSW]). Participants 1 to 10 performed postural tasks with sequence A (walking/sitting/BWSW) and participants 11 to 17 performed postural tasks with sequence B (BWSW/sitting/walking). Positive values indicate clockwise tilt of the VV (same direction as the VTR). B. Box plot representation of VV orientation in VTR for each postural condition. Positive values indicate clockwise tilt of the VV (same direction as the VTR). Data are median (Q1–Q3). ***$P < 0.001$ for the difference between VTR and darkness. No difference was found between postural conditions.

confirmed in every postural condition ($P < 0.05$). Of note, postural tasks had no effect on VV uncertainty, in darkness or in VTR.

7. Head orientation

The VTR induced a slight head tilt toward the tilted side (median: 3.3° [2.8–5.9]; $Z = -3.57$; $P < 0.001$) at baseline, with a large effect size attributed to the VTR ($r = 0.87$) (Fig. 6A) and in every postural condition ($P < 0.001$) with a similar magnitude. For VV, interesting results were found regarding head orientation in darkness (Fig. 6B): the head was upright at baseline ($Z = -1.54$; $P = 0.13$) but tilted toward the VTR during sitting ($Z = -2.11$; $P = 0.03$; $r = 0.51$) and walking ($Z = -2.01$; $P = 0.04$; $r = 0.49$), with large to medium effect sizes attributed to the postural condition. For VV, these findings indicated the existence of a post-effect of the VTR, lasting about 6 min. BWSW was the only condition under which the head orientation did not significantly differ from the Earth vertical ($Z = -1.59$; $P = 0.12$). Therefore, walking with partial BWS improved the active head orientation with respect to gravity.

8. Discussion

This study is the first to show that quasi-freely walking in a tilted immersive virtual environment is feasible, which should offer interesting clinical perspectives for patients for whom postural and gait disorders are due to a wrong internal model of

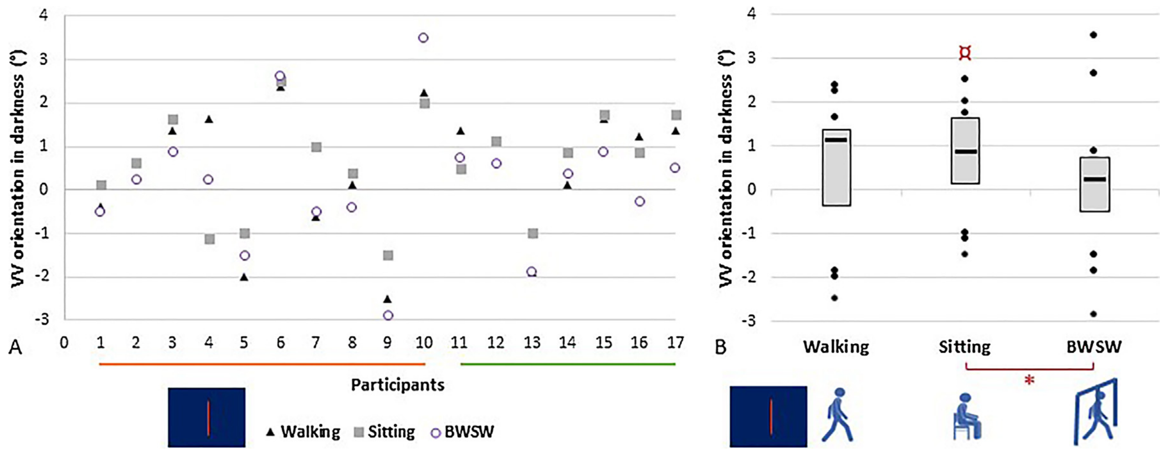

Fig. 5. A. Individual VV orientations in darkness for each postural condition (sitting, walking and BWSW). Participants 1 to 10 performed postural tasks with sequence A (walking/sitting/BWSW) and participants 11 to 17 performed postural tasks with sequence B (BWSW/sitting/walking). Positive values indicate clockwise tilt of the VV (same direction as the VTR). B. Box plot representation of VV orientation in darkness for each postural condition. Positive values indicate clockwise tilt of the VV (same direction as the VTR). ¤$P = 0.076$ tendency to differ from 0, to be significantly tilted; data are median (Q1–Q3). *$P < 0.05$ between postural conditions.

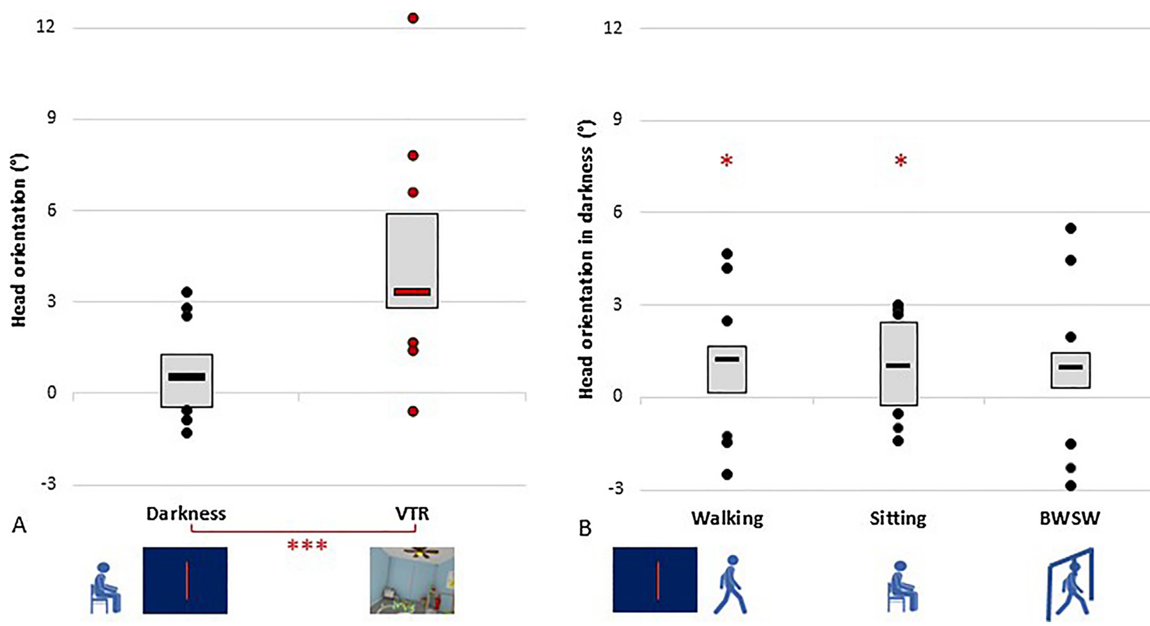

Fig. 6. A. Box plot representation of head orientation in darkness and in VTR, measured at baseline. Positive values indicate clockwise tilt of the head, same direction as the frame tilt. ***$P < 0.001$ between VTR and darkness. B. Box plot representation of head orientation in darkness for each postural condition. Positive values indicate clockwise tilt of the VV, same direction as the frame tilt. *$P < 0.05$ as compared with 0. Data are median (Q1–Q3).

verticality. More precisely, this study reveals the powerful and sustainable effect of the immersion in VTR creating a marked bias of the internal model of verticality, with a post-effect only suppressed by BWSW. However, 15% of healthy participants could not complete the experiment because of dizziness or likely eye torsion (outlier value of VV) and the tolerance might be lower in fragile patients. Technological improvements will be necessary to attenuate the VR discomfort in terms of using this technology to recalibrate the sense of upright in clinical trials.

9. Ranges of normality for VV tested with a VR device, head free

Our study gives a first indication about ranges of normality for VV tested with a VR device: -1° to $+1^{\circ}$. This range appears narrower that what is usually considered [22] and suggests that VV estimates obtained with this type of device are not noisy. It also suggests that the head and trunk do not need to be fixed as is usually done with standard procedures [22], at least in healthy controls [23]. One may even wonder whether the characteristics of the visual line might positively affect the quality of the test, considering that the size of the visual line was unusually large, projected in the far space, thus giving an unusually large angular size. Further investigations are needed to fully analyze the clinimetric properties of this test and compare them to those reported with other ways to test VV [22]. For uncertainty, ranges of normality obtained in this study were comparable to that already described [2,11,22].

10. VV modulation by a VTR

As hypothesized, immersing participants in a VTR strongly modulated the internal model of verticality, with a great inter-individual variability similar to what is found with usual devices [14]. We did not find any effect of age, sex or physical activity level on the VV bias. These results are in line with the theory of the perceptual trait or cognitive style mediated by central reweighting of the sensory inputs involved in spatial orientation. The magnitude of the modulation (median: 11°) was twice stronger than that found with other types of devices eliciting non-immersive 3D environments [14,16,28,29] and similar to that obtained with participants inside an actual tilted room [17]. These strong effects supported by a large effect size were predicted by the fact that we optimized several factors well known to enhance modulation of the VV by tilting the environment: the richness and meaningfulness of the indices of the environment about the vertical [6,15,30], the angular size of the material displayed [31,32] and the tilt of the environment, about 18° for a maximal effect [14,15].

Immersion in VTR increased the uncertainty about verticality perception, likely caused by a mismatch between visual and postural information [2,11]. However, this uncertainty remained below the 3° threshold established for verticality perception under standard conditions [22].

Post-effects on VV have never been investigated with modulation obtained by tilting the environment. We found a significant post-effect, lasting about 6 min. This finding was attested by the head, which was tilted clockwise in darkness, 6 min after the last immersion in VTR (in sitting and walking) and reinforced by the tendency for a VV bias toward the tilted side of the VTR found in darkness (in sitting). These tilting effects were strong during the immersion and their persistence in darkness may be explained only by an insufficient time between visual conditions to attenuate the tilting room effect. The darkness condition was always preceded by 2 min in the virtual room oriented upright. This situation could have interrupted the post-effect induced by the VTR, which was not the case. However, the effect was likely attenuated and underestimated. Its persistence under these conditions is another argument to use VTR for recalibrating biased representation of the vertical in rehabilitation and benefit from a post-effect.

11. VV modulation by BWSW

Krewer et al. [12] showed that a single session of gait aided by use of a robot reduced lateropulsion after stroke. Because lateropulsion is a postural behavior referring to a biased internal model of verticality [33], this improvement may have been mediated by an improvement of the internal model of verticality with the action of walking helped by a device giving the true Earth vertical. By showing with 2 congruent findings that BWSW modulated the internal model of verticality, our study favors this interpretation. First, BWSW in darkness reduced by 0.7° the VV bias resulting from the post-effect of the immersion in VTR, which tends to appear in sitting. Second, BWSW allowed the head to be kept straight in darkness, despite the post-effect of the repeated immersion in VTR visible in sitting and walking, when the head was attracted to the side. Contrary to our second hypothesis, the BWSW did not significantly attenuate the VV tilt induced by the VTR. However, this finding does not disprove our hypothesis, because BWSW suppressed the post-effect induced by the VTR and was the only postural condition in which the VV and head were kept upright in darkness. These findings are sufficient to prove that BWSW modulates the representation of verticality. We assume that when subjects were immersed in the VTR, the lack of BWSW effect was due in part to the powerful VTR effect, magnified by the fact that we used a same visual modality to manipulate and test the verticality perception, which led to large size effect, reaching almost 1. We realized *a posteriori* that conditions were not optimal to allow the BWSW to counterbalance the VTR effect. Although the magnitude of the BWSW effect in darkness was relatively weak, the effect sizes were medium. A stronger effect might be obtained with a non-visual modality of verticality perception. Further studies are needed to test the VTR on the postural perception of the vertical.

Participants walked suspended wearing a harness, with 3 points of pressure linked together by shoulder straps to a cross bar hooked to the device by a cable. This situation gives augmented information about the direction of the vertical because of several factors. The cable that supports the body is oriented to the Earth vertical, which is used by the brain as a stable and objective referential of verticality. It is subjected to tension (30% body weight), which magnifies the contribution of the somaesthetic graviception. Indeed, this tension is transmitted to the harness, which increases the body pressure as well as the cutaneous pressure, so the somaesthetic graviception is more accurate in involving tactile and interoceptive information [2,33,34].

The fact that participants were able to freely walk on the treadmill (without BWS), with their VV biased by 11°, favors a clear dissociation between their egocentric and exocentric representations of verticality, as was shown previously [11,33,35,36].

Our study also revealed interesting findings regarding head orientation. The head was moderately tilted toward the direction of the VTR (3° more than in darkness), an effect previously described with the rod and frame test [14,37]. Similar to that found for VV orientation, the head was more tilted in our study than in previous studies (about 1.2°), presumably because of the stronger effect induced by the VTR. We do not think this finding could have biased the results for the VV, given that a 3° head tilt is too small to markedly affect the VV [15,23,24]. This head tilt was minor in terms of the 11° VV tilt induced by the VTR, which could not be fully explained by the head tilt. Head orientation depends, at least in part, on the internal model of verticality. Head orientation was affected by the postural task. The head tilt found in sitting and walking in darkness resulted from a biased internal model of verticality caused by a post-effect of the VTR. BWSW was the only condition in which the head remained upright in darkness. Therefore, walking suspended improved the active head orientation with respect to gravity, a finding that should have a clinical impact because the head is a stable segment preferentially oriented upright for consistent vestibular and visual information [38], to optimize the control of dynamic balance [38,39]. Finally, together with the congruent findings reported for VV, this finding shows that walking suspended may recalibrate a biased internal model of verticality.

We also expected that the condition BWSW might decrease the VV uncertainty, which was not the case, likely because the uncertainty remained very low under all conditions.

12. Study limitations

Sequences of VV evaluation were often followed by a feeling of slight discomfort. This discomfort corresponded to the time when the visual environment switched from an adaptive orientation resting on head movements, to respect the absolute gravity referential and finally to fixation on a referential related to head axis. It disrupted the visual feedback on head and body movements, which led to the discomfort. This observation must lead to software improvements. We may wonder if the absence of optic flow when walking on a treadmill might have contributed to discomfort in some subjects. Further studies might integrate a more dynamic-oriented surrounding with an optic flow coupled to the treadmill speed, as used by Fung et al. [40].

For safety reasons and to feel secure, participants were invited to handle handrails during the walking tasks. These additional haptic cues during locomotion were not quantified and could vary among individuals. We cannot exclude that this use might mask a

BWSW effect because participants probably more firmly held the handrail under non-supported walking. In contrast, this use could not explain the great inter-individual variability shown in Fig. 3 because this variability was explored at baseline during sitting, a condition performed without handrails.

This was an exploratory study with a relatively few number of healthy participants, conducted ahead of a clinical trial in stroke patients showing postural and gait disorders due to a wrong internal model of verticality. However, the significant differences and the medium to large effect sizes confirm that the sample size was adapted for such a pilot study with use of non-parametric statistics. Postural perception of the vertical and lateropulsion should also be investigated in further studies.

13. Conclusion and perspectives

This pilot study reveals that immersing a subject in a VTR induces a powerful modulation of verticality perception, with a magnitude twice greater (11° than that obtained with a simple tilted frame, with large effect size and a post-effect. This virtually tilted surrounding did not preclude performing a dynamic task such as walking on a treadmill, probably because it elicited dissociation between egocentric and allocentric references of verticality. Of note, walking suspended is able to clearly recalibrate the internal model of verticality, the effect of which should be quantified with a design less oriented on visual manipulation than that of the present study. These findings appeal to clinical trials involving virtual reality and body-weight support walking to attenuate post-stroke lateropulsion.

Disclosure of interest

AO, DFP, and DP declare that they have no competing interest. FA is director of Virtualis who partially supported the study (equipment), without influencing the scientific content of the study. AO, DFP and DP are grateful to the Association Handinnov for its financial support for the study.

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