



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

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UNIVERSITÉ GRENOBLE ALPES  
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Modèle interne de verticalité : Neuro-modulation par la réalité virtuelle et la marche en suspension

THÈSE  
PRÉSENTÉE POUR L'OBTENTION DU TITRE DE DOCTEUR EN MÉDECINE  
DIPLOME D'ÉTAT

Dominique FALETTTO

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## **Résumé:**

Le développement de techniques de rééducation capables de recalibrer le modèle interne de verticalité est un enjeu majeur pour la prise en charge des troubles de l'équilibre et de latéropulsion. Cette étude pilote avec des sujets sains a pour objectif de tester deux techniques qui pourraient moduler la perception de la verticale : l'immersion dans un environnement virtuel incliné (VTR) et la marche en suspension (BWSW). 20 individus sains ont participé à cette étude, dont 12 pour qui nous avons analysé les données, âgés de 53.3 ans  $\pm$  7. Nous avons étudié les critères suivants : la verticale visuelle (VV) de base et immergée en environnement virtuel incliné. Huit mesures de verticales visuelles ont été réalisées pour chaque condition posturale (assise, marche sur tapis roulant et BWSW avec 30% du poids du corps) et chaque condition visuelle (obscurité et VTR). L'environnement virtuel incliné (de 18° vers la droite) est réalisé grâce à un masque de réalité virtuelle Oculus Rift®. Le schéma d'étude a pour but de créer un biais de perception de la VV par l'immersion en réalité virtuelle puis d'évaluer l'effet de la marche en suspension sur le biais créé. Nous retrouvons un effet majeur de la VTR sur la perception de la verticale avec la création d'un biais de 11.0°  $\pm$  4.4° ( $p < 0.001$ ) dans le sens d'inclinaison de l'environnement, une taille d'effet proche de 1 et un post effet à plus de 6 min. Nous retrouvons également un effet fort de la marche en suspension avec une atténuation du biais créé par la VTR ( $p < 0.05$ ).

Chez le sujet sain, l'immersion en VTR induit un biais majeur de perception de la VV, le BWSW permet d'augmenter les informations antigravitaires reçues. Modulating internal model of verticality by virtual reality and body-weight support walking: a pilot study in healthy participants

## **Abstract:**

The development of rehabilitation techniques modulating the sense of verticality is a major challenge for balance disorders such as lateropulsion after hemisphere stroke. With this pilot study in healthy participants, we tested two techniques that should modulate verticality perception: immersion in a tilted virtual environment (visual cues) and body weight support walking (BWSW, somaesthetic cues). Among 20 recruited healthy participants, 12 were studied ( $53.3 \pm 7$  years old) for the following criteria: normal visual vertical (VV) at baseline and sensitivity to an immersive virtual tilted room (VTR) without dizziness. The VV (8 trials) was tested in 3 postural conditions (sitting, treadmill walking, and BWSW with 30% body weight suspended by a vertical cable), with 2 visual conditions (darkness and VTR). The VTR ( $18^\circ$  clockwise tilt) was produced by wearing an Oculus Rift® head-mounted. The study design aimed at inducing a VV bias by use of the VTR, then testing the effects of postural conditions, especially BWSW, to correct this bias. We found: a main effect of the VTR on VV ( $11.0 \pm 4.4^\circ$ ;  $p < 0.001$ ), with the effect size close to 1, and an after-effect of several minutes; a strong effect of postural setting with the VV more vertical during BWSW than sitting ( $p < 0.05$ ). In conclusion, being immersed in a tilted environment induces a powerful bias in verticality perception. BWSW brings augmented information about the direction of the Earth vertical, which may correct the internal model of verticality if needed. These findings represent an avenue for rehabilitation of patients with postural disorders caused by a wrong verticality representation.

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## **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 development of rehabilitation techniques modulating the internal model of verticality is a major challenge in balance disorders related to lateropulsion or retropulsion (stroke, Parkinson disease, etc.).

We have abundant literature on modulating the internal model of verticality with sensory stimulation. Manipulating static (3,4) or dynamic (5,6) vision is long known to have a powerful effect on perception of the vertical. Many sensory stimulations that modulate the internal model of verticality interact with balance control, especially for dynamic visual stimulation (5,6), galvanic vestibular stimulation (7,8), or somaesthetic stimulation (2,9–13). Static visual manipulation has the advantage of strongly modulating the internal model of verticality without interfering with postural stabilization (14). As compared with previous techniques, direct transcranial brain stimulation might have a weaker effect on verticality perception (15).

A static tilt of the environment modulates verticality perception and attracts the visual vertical (VV) to the side with maximum effect for a frame tilted between 15° and 20° away from the vertical (14,16). The effect is stronger with cognitive and structural enrichment via 3D information (16,17) or by immersion in a real tilted environment (4,6,18). In the rehabilitation context, immersing patients in a true tilted room is not feasible, but new technologies should allow for such immersion in a tilted virtual environment. This possibility remains to be tested given that no study has ever tried to modulate the internal model of verticality this way. With this study we tested the hypothesis that complete 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.

No specific rehabilitation program dedicated to the sense of verticality has ever been validated, but some avenues look interesting. Viewing lateropulsion throughout the prism of verticality perception allows for possibly attenuating lateropulsion through somatosensory manipulations. Two papers have shown the interest of somaesthetic stimulation for reducing post-stroke lateropulsion. In patients with a biased postural vertical, Pérennou et al. found improved body verticality under transcutaneous electrical stimulation (10). A recent study found an immediate after-effect of body-weight support walking (BWSW) on diminishing lateropulsion in patients post-stroke (12). Together with the strong association between sensory loss and lateropulsion severity on one hand (10) and the strong contribution of somaesthetic graviception to the internal model of verticality on the other (19), these findings favor the use of somaesthetic manipulations to improve postural control in patients with a biased internal model of verticality. The second hypothesis tested in this pilot study was that by giving the brain relevant feedback about the Earth vertical during performance of a dynamic postural task, BWSW modulates the construction of the internal model of verticality via the vertical tension provided by the suspension cable.

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

## **Methods**

### **1. Participants**

Because of the novelty of this study, the sample size could not be calculated but was targeted at about 12 participants, which is usually sufficient for concluding verticality perception in experimental studies (18), and should be adapted to prepare a further randomized clinical trial in patients. We anticipated that some participants might fail to complete the experiment because of its supposed difficulty (walking on a treadmill in darkness or the VTR, while setting a visual line to the vertical) or possible adverse effects (vertigo induced by the VTR). To eliminate any biased data from the final analysis, we *a priori*



decided to discard data for any participant who might have difficulties completing the experiment, experienced vertigo during the immersive VTR, or showed a VV beyond the usual normal range (i.e.,  $\pm 2.5^\circ$ ) at baseline (20) due to unusual testing with a head-mounted display (HMD). As well, we discarded data for participants in whom VV was insufficiently modulated by the VTR. Indeed, the idea of the study was to experimentally create a VV tilt by using a VTR, then to examine how walking suspended or not might attenuate this bias. This hypothesis could not be tested in patients in whom VV was insufficiently modulated by the VTR.

We recruited 20 healthy participants among our staff members and their relatives. All were naive to the study hypotheses, and none was an expert in a balance field (or an athlete). Criteria for inclusion were age over 35 years old (so as to conduct further studies in patients with stroke), no neurological or vestibular history, no cognitive or psychiatric disorders and/or gait disturbance. All gave informed consent and the study was performed in compliance with the Helsinki Declaration.

All 20 participants were able to perform the whole experiment, but data for 8 were excluded from the study: 2 with baseline VV beyond the normal range, 1 for dizziness, and 5 with data below the first quartile of VV distribution with the VTR (Figure 1). For the 12 participants included in the study, the mean ( $\pm$ SD) age was  $53.3 \pm 6.8$  years (7 women); mean body weight and height were  $72.7 \pm 18.0$  kg and  $1.71 \pm 0.10$  m; and baseline VV was  $0.4 \pm 0.9^\circ$ .

## **2. Study design**

Given the limited sample size and to increase statistical power, the study design was crossover with multiple conditions (Figure 2). First, baseline VV was assessed in a sitting position, head and trunk free, after 2 min spent in darkness (HMD worn but off). Then, VV was tested in 2 visual conditions (darkness or immersive VTR) and 3 postural conditions (walking, sitting or BWSW). Half ( $n=6$ ) of the participants performed Plan A (walking, sitting, BWSW) and half ( $n=6$ ) performed the reverse order (BWSW, sitting, walking) called Plan B.

This design aimed at avoiding any effects or aftereffects related to learning or fatigue.

Participants were pseudo-randomly allocated to Plan A or B, and their characteristics were similar. The sitting task was systematically performed between the 2 walking tasks to serve as resting phase. Each postural task was started in the same virtual surrounding (displayed by the HMD) as that presented for the VTR, that time verticality oriented. This precaution allowed for better control of visual cueing and preventing possible dizziness feelings induced by walking in darkness. VV was tested after 2 min, in darkness first, then in the VTR. The experiment lasted about 45 min and consisted of 64 VV measurements (8 blocks of 8 measurements), and ended by a structured interview to ask about any adverse effects experienced: dizziness, virtual reality sickness, discomfort due to the harness, fear of falling, etc.

### **3. Experimental conditions**

#### *Visual surrounding*

Throughout the whole procedure, participants wore the Oculus Rift DK2® HMD (Oculus, Menlo Park, CA, USA) that delivered the VV evaluation module generated by the software PosturoVR 0.8.3 (Virtualis, France). The virtual reality HMD was 1920 pixels wide  $\times$  1080 pixels high (960  $\times$  1080 per eye) with a 100° field of view. We used two immersive environments: a dark-blue background comparable to darkness, without visual clues available, or a VTR. The virtual scene (Figure 2) was a bedroom, 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 (16). The tilted orientation of the scene was stabilized on the Earth-vertical regardless of head orientation owing to the gyrometer of the device. Only the clockwise direction was chosen so as to simplify the protocol and for further studies of people with a right-hemisphere stroke and the hypothesis that immersing them in an appropriate VTR would recalibrate their pronounced counterclockwise VV tilt (19).

### *Postural tasks*

Participants wore a harness during the protocol, to perform the experiment more safely and quickly, and to avoid biasing data by wearing the harness only in the required condition (BWSW). We used a commercialized unweighing harness (Biodex Company, Shirley, NY, USA)

with 3 points of pressure (hip straps, gluteal fold straps and lumbar-thoracic harness) with 2 shoulder straps suspending each hemibody to the ends of a cross bar, itself hooked to the framework in a single-point suspension (Figure 2).

In sitting, participants were seated without back support on a chair placed on the treadmill, which was immobile. Their hands were laid one on the other on their thighs and their head and trunk were free. We chose not to use a chin rest in none of the three postural conditions because this was not possible for walking. This also allowed us to monitor the head orientation. For the 2 walking conditions, participants walked on a RTM600™ treadmill device at comfortable speed (3k m/h). In the suspended condition, 30% bodyweight was unloaded by use of a cable hooked to the single-point suspension of the harness (Figure 2), therefore submitted to vertical tension. Because of the supposed difficulty of walking on a treadmill while being immersed in a VTR and for safety reasons, all participants were asked to hold onto the handrails of the device under both walking conditions (Figure 2). In addition, the experiment was supervised by 2 people, one responsible for safety and remaining close to the treadmill and ready for an emergency shutdown and the other responsible for data acquisition.

### **4. Criteria**

*VV orientation*, called VV, was the primary outcome of the study. Participants were asked to orient a line vertically by giving oral instructions to the examiner. Starting positions were randomly presented from  $-80^{\circ}$  to  $80^{\circ}$ . Each session involved 8 trials, and VV was calculated as the average of each block (2 blocks per postural conditions). We thus obtained a robust

result (21) while limiting the time spent in virtual reality. The study involved no time constraints or performance feedback between measures. Before completing the protocol, participants were familiarized with the experimental setup and performed 2 practice trials. By convention, a positive value corresponded to a VV tilt oriented toward the VTR. VV orientation was measured in terms of the Earth vertical with the gyrometer of the device. Step-width was  $0.2^{\circ}$ .

*Head orientation* was the second criteria. To analyze the possible influence of a VTR on head orientation in the 3 postural conditions, given the well-known influence of head orientation on VV (22,23), and since the head had to remain free not to interact with the BWSW, head orientation had to be controlled. The mean head orientation during each block of VV was thus monitored by use of an on-board accelerometer and gyroscope combined in one sensor: an accurate gyrometer. This measured head orientation with a  $0.01^{\circ}$  accuracy. By convention, a positive value corresponded to a head tilt toward the VTR.

## **5. Statistical analysis**

Statistical analyses involved use of SPSS v23 (IBM Corp., Armonk, NY, USA). All dependent variables were continuous with normal distribution (Shapiro-Wilks test). Descriptive statistics were generated for all variables. VV and head orientation in darkness were compared to the Earth vertical by using one-sample  $t$  tests. The model used to analyze the main effects was a 3-way repeated measures ANOVA on both VV and head orientation, with postural conditions (sitting, walking, BWSW) and visual surroundings (darkness, VTR) as within factors and sequences (A or B) as between factors. Mauchly's tests were performed. If the assumption of sphericity was not verified, Greenhouse-Geisser correction was applied. Bonferroni corrections were used for post-hoc analyses. Bilateral statistics were used, so  $\alpha$  risk was fixed at  $P < .05$ , and partial eta squared ( $\eta^2$ ) was used to quantify the effect size. As recommended by Cohen (1988), effect size  $> 0.02$  was considered low;  $> 0.13$ , medium; and  $> 0.26$ , strong. The experimental plan allowed for analyzing the existence of an aftereffect,

to understand whether visual neuromodulation lasted several minutes after the immersion in the VTR. Unless otherwise indicated, data are presented as mean $\pm$ SD.

## **Results**

### **1. Visual vertical orientation**

Data are presented individually in Figure 3 and by groups in Figure 4. The 3-factor ANOVA found no significant interaction between factors, nor any effect of measurement sequence.

In contrast, we found a main effect of the tilted room ( $F(1,10)=158.5$ ,  $p<0.001$  with partial  $\eta^2=0.94$ ), VV being tilted with the VTR (Figure 4A), and a strong effect of the postural setting ( $F(2,20)=5.4$ ,  $p<0.05$  with partial  $\eta^2=0.35$ ). Post-hoc analysis showed that the VV was  $0.6^\circ$  more vertical with partial BWSW than with sitting (95% CI  $0.01$  to  $1.3^\circ$ ;  $p=0.048$ ). Moreover, with or without BWS, walking tended to modulate VV and change it to more upright than did sitting (95% CI  $-0.3^\circ$  to  $0.9^\circ$ ;  $p=0.067$ ).

Given the powerful VV modulation by the VTR, we then analyzed possible post-effects by examining data under the darkness condition. Under darkness, the VV significantly differed from the Earth vertical only with sitting ( $t(11)=2.78$ ,  $p=0.018$ ; Figure 4B). The sitting condition was the third condition tested in the experimental plan and therefore always preceded by 2 immersions in the VTR. This finding indicates the existence of a post-effect, lasting for at least 6 min (Figure 2). With walking, VV was not affected by this post-effect (walking without BWS ( $t(11)=0.59$ ,  $p=0.57$ ) or partial BWSW ( $t(11)=1.24$ ,  $p=0.24$ ), which is consistent with the positive effect of walking on verticality perception.

### **2. Head orientation**

Head orientations are presented in Figure 5. The 3-factor ANOVA found a significant interaction between visual and postural factors ( $F(2,20)=3.6$ ,  $p=0.045$  with partial  $\eta^2=0.27$ ).

This interaction was explained by the opposite behavior of the head in the BWS condition. In darkness, the head tended to be more upright, whereas in the VTR the head was more tilted.

To further analyze data, the effect of the VTR was investigated for each postural condition by

paired  $t$  test. We found a VTR effect for each postural condition, with greater difference with the BWSW condition ( $t(11)=5.134$ ,  $p<0.001$  in sitting,  $t(11)=12.2$ ,  $p<0.001$  in walking and  $t(11)=8.6$ ,  $p<0.001$  in BWSW). The head was slightly more tilted in the VTR than in darkness, with a  $3.1^{\circ}\pm 0.3$  difference between the 2 visual surroundings.

## **Discussion**

This study is the first to show that walking in a tilted immersive virtual environment is feasible. It offers promising prospects for further research and rehabilitation programs. Moreover, this study reveals the powerful and sustainable effect of the immersion in VTR creating a marked bias of the internal model of verticality, which can be partially corrected by BWSW.

### **1. VV modulation by a VTR**

As hypothesized, visual manipulation with the VTR strongly modulated the internal model of verticality. More precisely, the VV alteration was  $11^{\circ}$ , at least twice stronger than that found with other types of devices eliciting non-immersive 3D environments (14,17,24,25). The effect size we found was 0.94, which is almost the maximum effect size possible. The amplitude of the effect we obtained with the VTR was similar to that obtained by Singer and Purcell with an actual room tilted to  $22.5^{\circ}$  (18). These strong effects were predicted by the fact that we optimized several effects 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 (6,16,26), the angular size of the material displayed (27,28), and the tilt of the environment, about  $18^{\circ}$  for a maximal effect (14,16).

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 existence of a remaining VV bias in darkness in sitting. This post-effect might have clinical interest.

### **2. VV modulation by walking suspended**

In 2013, Krewer et al. (12) showed that a single session of gait aided by use of a robot reduced lateropulsion after stroke. Since lateropulsion is a postural behavior referred to as a biased internal model of verticality (19), this improvement may have been mediated by an improvement of the internal model of verticality with the action of walking with 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, the BWSW reduced by  $0.6^\circ$  the bias induced by the VTR. Second the BWSW suppressed the post-effect of the VTR found with sitting in darkness (amplitude  $0.7^\circ$ ). In both cases, the magnitude of the effect approached  $1^\circ$ . This magnitude might be considered relatively weak. However, we do think these effects are important. First, the size effect was estimated with a partial  $\eta^2$  of 0.35 which is interpreted as strong (29). Second, these effects had to counterbalance a very powerful VV modulation by the VTR, with a study design privileging the visual modality on the somaesthetic one (VV is visual material to be oriented in a specific visual environment). Furthermore, because participants were able to freely walk on the treadmill (walking without BWS), with their VV biased by  $11^\circ$ , their egocentric and exocentric representations of verticality were clearly dissociated, as was shown previously (11,19,30,31). The effect of BWSW might be greater on the postural than visual perception of the vertical, which was not assessed in this study and remains to be investigated.

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 (2,19,32).

Walking without BWS tended to modulate the verticality perception. In line with the ecological theory of orientation adapted to postural control (33), several authors have suggested that the action against gravity itself might help build the internal model of verticality (10,33–35), in interaction with alert and attentional systems (11,36). These theoretical aspects might find an application in neurorehabilitation, thereby suggesting the interest of early verticalisation in patients with a biased internal model of verticality, which needs further clarification.

Our study also revealed interesting findings regarding head orientation. The head was moderately tilted toward the direction of the VTR ( $3^\circ$  more than in darkness), an effect previously described with the rod and frame test (14,37). Similarly to that found for VV, the head was more tilted in our study than in previous studies (about  $1.2^\circ$ ), presumably because of the stronger effect induced by the VTR. We do not believe this finding could have biased the results for the VV, given that a  $3^\circ$  head tilt is too small to influence the VV (16,22,23). In addition, this head tilt was minor in terms of the  $11^\circ$  VV tilt induced by the VTR, which could not be explained by the head tilt. Head orientation was also influenced by the postural task. When the trunk was supported (BWSW condition) the head tended to be more tilted. In fact, in that condition, the stable platform used to control balance was the trunk (being maintained upright), and the head could more freely accept the attraction induced by the VTR. Without BWS, the head had to contribute to balance and had to be oriented as upright as possible (38).

### **3. Study limitation**

This is an explanatory study with a relatively few number of healthy subjects. However, these limitations were attenuated because the study was driven by 2 clear hypotheses and conducted with an experimental plan increasing the statistical power and allowing for comparing 2 visual and 3 postural conditions and analysing interactions. The highly



significant differences and very strong effect sizes confirm that the sample size was adapted for such a pilot study. Postural perception of the vertical and lateropulsion needs to be investigated in future studies, and the effect found with walking needs to be extended to other dynamic tasks against gravity.

(\*) THESE SOUTENUE PAR : Dominique Marie Thérèse Pascale FALETTO

(\*) TITRE : Model interne de verticalité : Neuromodulation par la réalité virtuelle et la marche en suspension

(\*) CONCLUSION

This pilot study reveals that immersing a subject in a virtual tilted room induces an extraordinary modulation of verticality perception, with a magnitude ( $12^\circ$ ) twice greater than the effect obtained with a simple tilted frame, an effect size close to 1, and a post-effect. However, this virtually tilted surrounding does not preclude performing a dynamic task such as walking on a treadmill, probably because it elicits a dissociation between egocentric and allocentric references of verticality. Of note, postural actions against gravity seem to contribute to building the internal model of verticality, an effect magnified when the body is partly suspended (30%) while walking on a treadmill. These findings appeal to clinical trials involving virtual reality and body weight support walking to attenuate post-stroke lateropulsion.

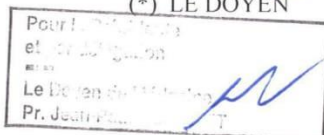
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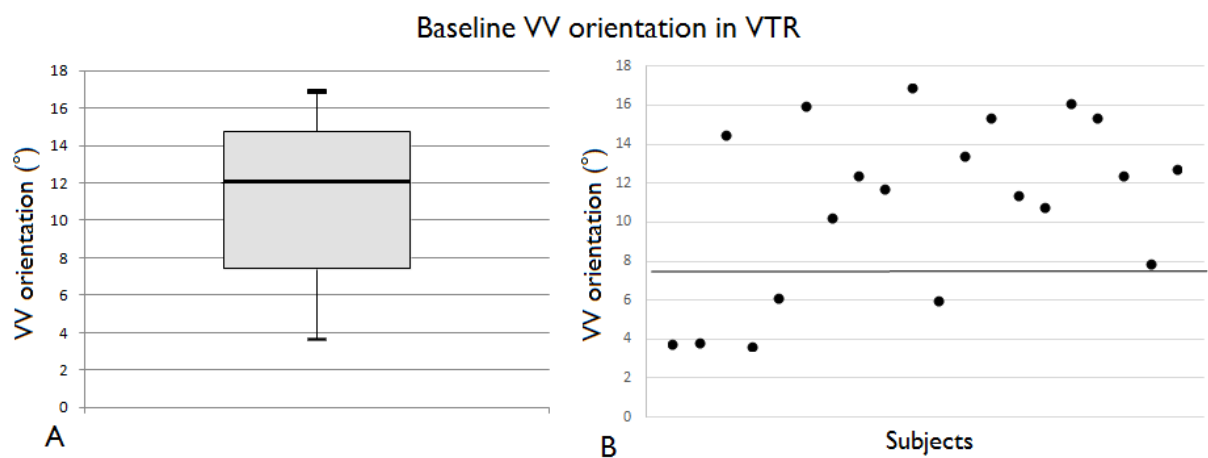


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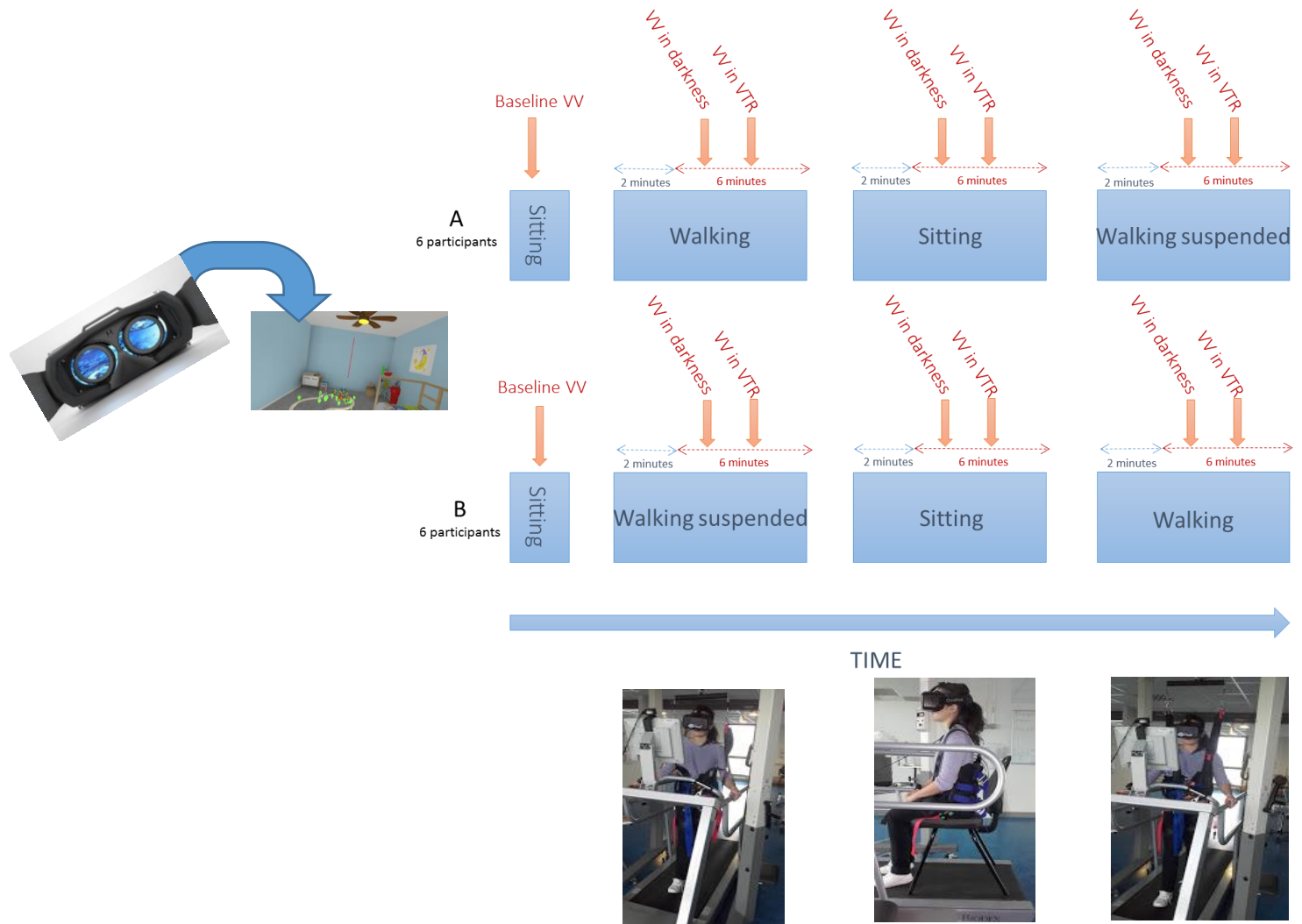
(\*) PROFESSEUR Dominic PERENNOU

## **Figures**

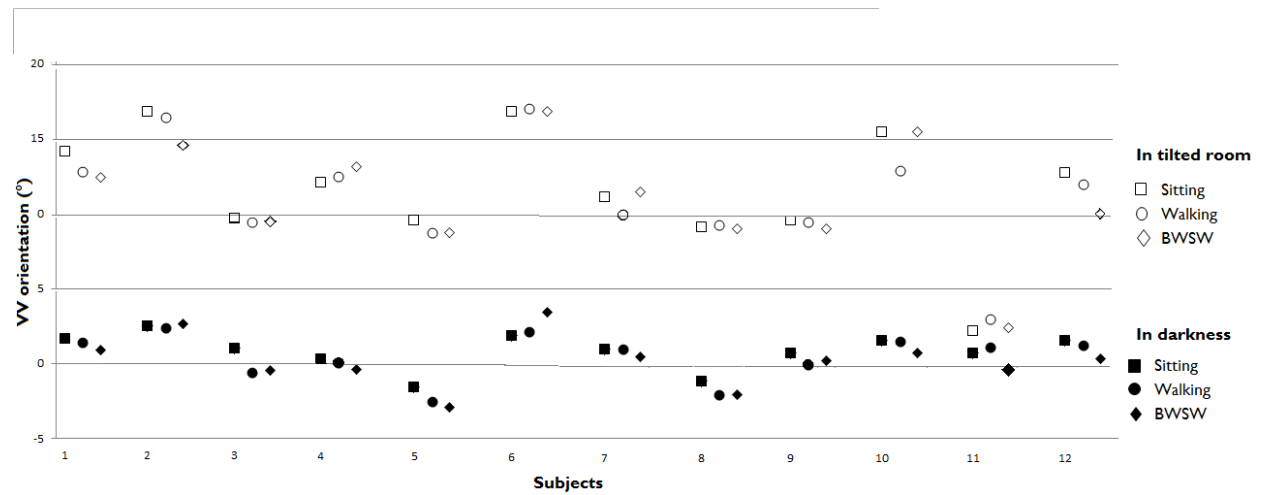
**Figure 1.** **A)** Box-plot representation of initial visual vertical (VV) orientation in the virtual tilted room (VTR) for all 20 subjects. **B)** Individual data for the VV experimental biases induced by the immersive VTR. The line represents the first quartile, below which the effect induced was considered insufficient to support the experiment. Data for participants who were considered to resist modulation of their sense of verticality were not included in the study.



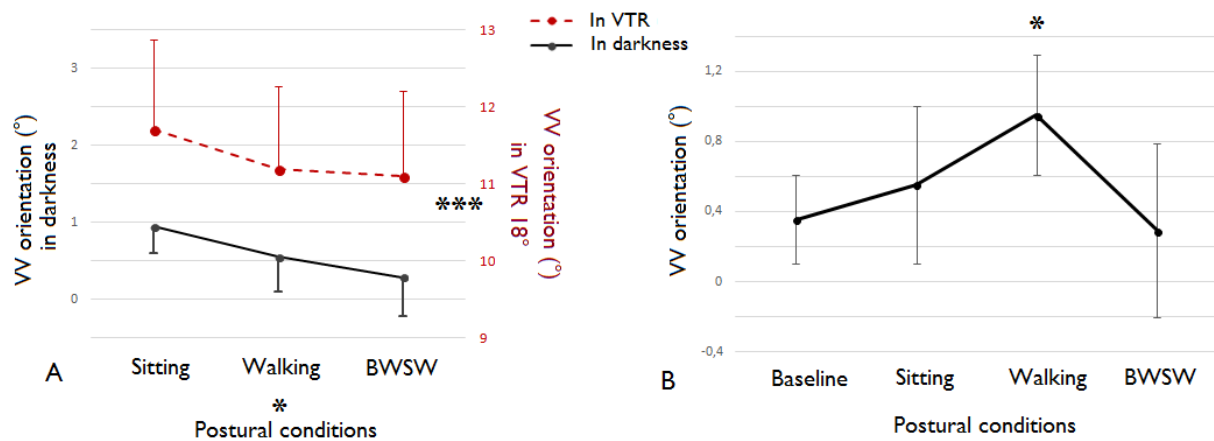
**Figure 2.** Protocol diagram with VV evaluations in red and postural tasks in blue. Participants were pseudo-randomized 1:1 in 2 orders, A or B, with postural tasks performed in the reverse order.



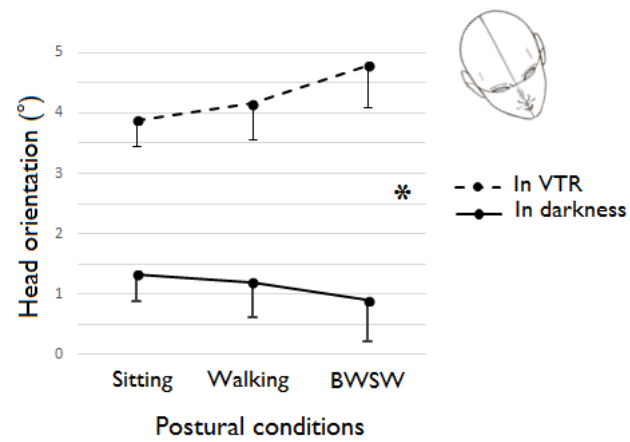
**Figure 3.** Individual VV orientations for the 12 participants as a function of the visual condition (darkness or VTR) and postural condition (sitting, walking and body-weight support walking [BWSW]). Positive values indicate clockwise tilt of the VV, same direction as the frame tilt.



**Figure 4.** A) VV as a function of visual condition (darkness or VTR) and postural condition (sitting, walking or BWSW). Positive values indicate clockwise tilt, same direction as the frame tilt. Data are mean (SE). \*:  $p < 0.05$ ; \*\*\*:  $p < 0.001$ . B) VV in darkness, baseline evaluation and evolution with the different postural settings (sitting, walking or BWSW) ranked in temporal order. Data are mean (SE). Positive values indicate clockwise tilt, same direction as the room tilt. \*:  $p < 0.05$ , the value differs significantly from 0.



**Figure 5.** Head orientation recorded during each evaluation session as a function of visual condition (darkness or VTR) and postural condition. Data are mean (SE). \*:  $p < 0.05$  for visual and postural factor interaction.



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