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Functional relation between postural sway and saccadic eye movements is strong and not altered by moving visual environment and concomitant memory task

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ABSTRACT

We investigated whether the adaptation of postural control to perform saccadic tasks is still maintained in challenging situations such as when the posture is challenged with a large movement of the moving room and with the addition of a second perturbation as a visual task of memorization. Thirty young adults (20.0 ± 1.3 years) were randomly assigned to the control and experimental groups. Participants stood upright on a force plate inside a moving room wearing eye-tracking. The room moved back and forth (anterior-posterior direction), at low (0.6 cm - first and third trials) and high (3.5 cm - second trial) amplitude, and frequency of 0.2 Hz. In each trial, participants performed left-right horizontal saccades on a target (1.1 Hz). Experimental group also performed a concomitant number memorization task. There were no differences between groups in the coupling between center of pressure (CoP) displacements and visual stimulus in any condition. There was also no difference in the performance of the saccadic task. In the memorization task, CoP displacements in response to the visual stimulus frequency (room motion) were not affected. The performance in the memorization task was similar between room conditions. Overall, increasing cognitive involvement by adding a working memory task does not deteriorate the postural stabilization of young adults to accomplish accurate gaze shifts. Also, it does not interfere with adaptive visual reweighting due to changes in the moving room amplitude. In conclusion, young adults are flexible in optimize their postural control to succeed in multiple tasks even under perturbation.

Keywords: Postural control, visual perturbation, saccades, visual memory, eye movements.

1. INTRODUCTION

In everyday life, performing motor tasks require the central nervous system (CNS) to dynamically integrate multiple perceptual and motor components (i.e., sensorimotor coupling) to achieve the desired orientation and position of the body (Asslander & Peterka, 2014; J. A. Barela et al., 2014; Carver et al., 2006; Huxhold et al., 2006). Maintaining flexible and context-related postural control is crucial for achieving motor tasks considering ongoing changes in environmental conditions and postural sway (Horak & Macpherson, 1996). Researchers have investigated the adaptation of postural control when performing visual tasks that involve saccadic eye movements. These studies demonstrated that postural sway is lower to facilitate the performance of precise gaze shifts towards a target or specific locations of the scene in comparison to control free-viewing tasks (Bonnet et al., 2019; Polastri et al., 2019; Rodrigues et al., 2013; Stoffregen et al., 2006).

The relationship between sway and visual information through visual manipulation (moving room) also has been investigated in different situations (Barela et al., 2009; Moraes et al., 2016; Polastri et al., 2012; Schoner et al., 1998). On the one hand, low amplitude and frequency (0.6 cm and 0.2 Hz) of the moving room (i.e., visual stimulus) significantly increase body sway (Barela et al., 2009; Barela et al., 2003; Oie et al., 2005) without changing the coupling between visual information and body sway (Aguiar et al., 2014). On the other hand, when the room's motion is increased to high amplitude (3.5 cm) and frequency (above 0.3 Hz), body sway also increases; however, the coupling between visual information and body sway is quickly reduced. These results demonstrate an adaptation of the postural control system to avoid postural instability (Barela et al., 2014).

Brito and colleagues. (Brito et al., 2021) investigated the adaptation of postural control in young adults examining how the CNS responds to continuous changes in visual flow while performing various gaze behaviors. Specifically, the participants performed visual tasks inside the moving room manipulated at low amplitude (0.6 cm) and low frequency (0.2 Hz). They were unaware of the room movement and instructed to perform a given visual task (gaze fixation and predictable saccadic movements to the right and left sequentially toward a target and unpredictable saccadic movements to the right and left randomly toward a target) while maintaining a quiet upright stance. When the room was moving, the results showed less variable CoP displacements during the unpredictable saccades task when compared to the gaze fixation task. Also, there was a longer reaction time of the eyes to the target during unpredictable saccades indicating how challenging was the gaze performance as compared to the predictable saccades task. Therefore, less variability in the coupling between visual information and postural sway during the unpredictable saccades task indicates fewer CoP displacements at other frequencies than the visual stimulus frequency provided by the moving room. It means that the CNS was highly responsive to the driving frequency (0,2 Hz) during this visual task condition which revealed the adaptation of the postural control system to succeed in the demanding target-oriented saccades.

In other words, the results of Brito and colleagues (Brito et al., 2021) showed that the CNS modulates postural control to deal with constraints of visual tasks (i.e., uncertainty of the target location). Indeed, the participants needed to stabilize their balance to look straight at moving targets (Brito et al., 2021). These findings indicate that not only are performed functional interactions between postural and gaze control in static sensory environments (Ginsburg & Cannon, 1980; Rodrigues et al., 2013; Stoffregen et al., 2006), but they are also in dynamic sensory environments.

Another important aspect is the potential impact of increasing the cognitive/attentional demands to posture and oculomotor control during challenging visual task performance. In particular, some studies imposing difficulty in the cognitive tasks (dual-task interference), challenging the bases of support, or providing external visual perturbations (e.g., moving room) showed ineffective postural responses due to additional cognitive efforts (e.g., Aguiar et al., 2014; Pellecchia, 2003; Salihu et al., 2022; Tixier et al., 2021). For instance, Aguiar and colleagues (2014) demonstrated that counting backward by three produced interference in the postural control dynamics when the participants were in the moving room. There was an increase in the influence of the room movement (i.e., higher visual gain) on the postural sway, especially during the condition in which the participants were warned about the visual perturbation and instructed not to oscillate with the room. As suggested by the authors, adding the cognitive task compromised the gathering of sensory information to produce appropriate motor commands to decrease the coupling between body sway and unreliable visual information provided by the room motion. In addition, Tixier and colleagues (2021) showed that postural control was worse (e.g., higher body sway variability) in an episodic memory task than in the control task supporting the idea that the level of cognitive/attentional demands of a secondary task account for significant impairment in the performance of one or both the tasks (Shumway-Cook & Woollacott, 2000). Hence, to build on existing science, we focus on the postural control adaptation to perform saccadic eye movement tasks with additional cognitive/attentional efforts.

The main purpose of the present study was to investigate whether the adaptation of postural control to perform saccadic tasks is still maintained in challenging situations, such as when the posture is challenged with a large movement of the moving room and with the addition of a second perturbation, such as a visual task of memorization. In addition, we tested whether the gaze control itself would be affected by the visual memory task and room motion. Thirty healthy young adults were exposed to changes in the amplitude of the visual stimulus provided by a moving room (low and high amplitude conditions) while performing saccadic eye movements, with and without a secondary visual memory task (experimental and control groups, respectively). As our experimental conditions were very challenging, we expected to find higher CoP displacement and gain of CoP sway relative to the room motion when performing simultaneously the visual memorization and saccadic task than when performing only the saccadic task. As such, we expected postural control adaptation to be very challenged with such double perturbations. We also expected that task performance in saccadic eye movements would be delayed (with longer eye response time) when performing simultaneously the visual memorization and saccadic task than when performing only the saccadic task.

2. METHODS

2.1 Participants

The total number of participants was determined using an a priori sample size calculation in the G*Power software. We use the F-tests (Test family) called ANOVA repeated measures, within-between interaction (Statistical test). The estimated effect size (f) was 0.25 (representing a medium effect size based on Cohen's f (Cohen, 1988)), an alpha of 0.05, a power of 0.8, number of groups was 2, the number of measurements was 3, correlation among repeated measures of 0,05 and nonsphericity correction of 1. This computation showed that we needed a sample size of 28 participants to get a significant effect. For this reason, thirty young adults (20.0 ± 1.30 years) participated in the present study. Of this total, fifteen participants were randomly assigned to the control group (age: 20.18 ±1.65; body mass: 66.63 ±13.72; body height: 1.66±0.075) and the other fifteen assigned to the experimental group (age: 20.45 ±2.02; body mass: 67.14 ±13.37; body height: 1.68±0.07). The control group performed a perturbed saccadic task (moving room condition), and the experimental group a simultaneous visual memory task in addition to the same perturbed saccadic task.

All participants had normal or corrected-to-normal vision. None of the participants reported neuromuscular problems, prostheses, vestibular or visual problems, use of medications, or diseases that could affect the ability to maintain an upright stance. Before the experimental procedures, participants were informed about the study and signed a written consent form approved by the local University Ethics Committee (CAAE: 82715518.0.0000.5398).

2.2 Equipment

The moving room consisted of three white walls covered with three vertical black stripes (20 cm wide), 35 cm apart (white area), and a white painted ceiling. The walls and ceiling were mounted on an aluminum structure (2.0 x 2.0 x 2.0 meters – width, height, and length). The floor inside of the room was completely covered by a black tarp (Figure 1). This structure was placed on rails, allowing the room to move back and forth but the floor to remain motionless. This movement was conducted by a controller (Parker Compumotor - Mod. 6k8) and a stepper motor (Mod. PL06) connected to the room's front wall. Specific programs (Compumotor - Motion Architect) were used to control room motion. A multimedia projector (EPSON Powerlite W6) was attached to the ceiling of the room, fixed back and above the participants' heads. The multimedia projector provided the images of the targets on the front wall. During data collection, the projector moved with the whole room structure, maintaining a constant visual angle.

A force plate (AMTI - AccuGait) was used to analyze the center of pressure (CoP) displacement throughout the trials. A head-mounted monocular eye tracker (model H6, Applied Science Laboratory, USA) was used to record the left eye behavior in all conditions. A magnetic movement analysis system composed of a transmitter, a receiver, and a control center (Flock of Birds Magnetic System) was used to measure the room displacements. The receiver was attached to the room's lateral wall on a piece of wood 25 cm long and 10 cm away from the transmitter. A speaker (ONEAL -OCM190) was placed to the side of the moving room and emitted a "white noise" sound to minimize any noise or specific sound due to the room's movement on the rails to avoid providing any additional information that could influence the postural response to the visual stimulus (Freitas Junior, Barela, 2004). All the apparatus (force plate, magnetic sensor, and eye tracker device) were synchronized and acquired with a sampling frequency of 60 Hz.

[INSERT FIGURE 1]

2.3 Procedures

The participants stood on a force plate, inside a moving room, using an eye tracker device positioned on their heads for calibration and synchronization of the equipment. To calibrate this system, the participants remained still as possible and fixated on a 3x3 points matrix displayed on the room's front wall. The calibration was checked before each trial.

The horizontal saccadic eye movement task consisted of directing the eyes towards a visual target. The participant fixed on a central target that disappeared and randomly reappeared to the right or the left sides, then disappeared to reappear in the center, and so on. The target position change was at a frequency of 1.1 Hz. The visual target was a white letter "X" displayed in the center of the projection area and a black-filled circle displayed on the right or left sides, both targets with a visual angle of 1.71°. The target colors contrasted with the white and black stripes covering the room's walls. The eccentricity of the target was 11.5° of visual angle. The participants performed the saccadic task with their eyes open. Studies have shown that angular distances below 15° are usually covered by eye movements and do not require head rotations (Land & Tatler, 2009; Proudlock & Gottlob, 2007).

The visual memorization task consisted of recalling how many times the number "6" appeared among a sequence of 30 random numbers ranging from 1 to 9. The numbers were displayed in white with a visual angle of 1.10 °. The numbers were presented within the black-filled circle target on the right and left sides for 900 milliseconds for the experimental group only. A total number of 6 could appear in one trial ranging between 7 and 9 times. Figure 2 depicts exemplars of horizontal gaze position during the saccades task of control and experimental groups. The participant was instructed to visually memorize the number without using any strategy, such as finger pressure on the leg or verbal recall. A visual memorization task was created to increase the cognitive load during the performance of the saccadic task since the number to be memorized was inside the target and also had to be acquired visually among various numbers.

[INSERT FIGURE 2]

Both groups (experimental and control) performed the saccadic eye movements task in the following room motion conditions: 1-) pre-low amplitude; 2-) high amplitude; and 3-) post-low amplitude, for a total of three trials per participant. Each trial lasted 60 seconds. For the room conditions, in the first trial, the room was moved with an amplitude of 0.6 cm (pre-low amplitude trial). In the second trial, the room was moved with an amplitude of 3.5 cm (high amplitude trial). In the third trial, the room was moved with an amplitude of 0.6 cm (post-low amplitude trial) (see Figure 3). In all trials, the room was moved at a frequency of 0.2 Hz. The design and amplitude parameters of the moving room (0.6 cm and 3.5 cm, respectively) were similar to previous studies (Barela et al., 2014; Polastri & Barela, 2013). These parameters were used to describe the changes in COP displacements before, during, and after an increase in the visual stimulus amplitude (moving room). The participants were unaware of the visual manipulation, i.e., room movement. This procedure allowed us to examine the unconscious adaptation of postural control due to changes in visual perturbations (Freitas Júnior & Barela, 2004).

[INSERT FIGURE 3]

The participants were instructed to stand as still as possible, with arms along the body, and direct their eyes towards the target displayed on the front wall of the moving room. The control group performed a double task, i.e., maintained their upright stance and performed the saccades task. The experimental group performed a triple task, i.e., upright stance, saccades task, and visual memorization. The experimenter remained close and behind the participants throughout the data collection.

2.4 Data analysis

For all dependent variables, room sensor and CoP raw data were filtered by a 4th order low-pass digital Butterworth filter, with a cut-off frequency of 4 Hz. Filter parameters were chosen based on previous studies which examined postural behavior in similar moving room conditions and visual tasks (Brito et al., 2021; Rinaldi et al., 2009). The overall mean amplitude of CoP displacements was computed as the standard deviation of the CoP time series after removing any linear trends by subtracting the first-order polynomial from the trajectory of CoP within each trial to examine changes in CoP displacements across all conditions and tasks. Thus, we performed the “detrend function” using a MATLAB software routine. This dependent variable was computed in anterior-posterior (AP) and medial-lateral (ML) directions.

A Frequency-Response Function (FRF) analysis was performed to quantify the amplitude of the postural responses to the room motion by dividing the Fourier transformations of the CoP trajectory by the Fourier transformations of the room trajectory at the stimulus driving frequency (0.2 Hz). It generated a complex-valued function for each trial (transfer function). Cycle by cycle of the FRF was determined at intervals of 5 seconds for each trial that correspond to the back-and-forth room motion, and then averaged across trials and groups. We calculated the following dependent variables: (a) gain

– the ratio between the room amplitude and CoP amplitude in the AP direction, computed as the absolute value of the transfer function. Gain values close to 1 meant that the CoP displacement was equal to the amplitude of the room, and it indicates a stronger coupling between visual information and CoP displacement; (b) phase – the temporal relationship between CoP displacement and room movement, computed as the “argument” of the transfer function, converted from radians to degrees. Positive phase values indicated that the CoP displacement is temporally ahead of the room movement, and negative phase values indicated that the CoP displacement lags behind the room movement. In addition to these variables, position and velocity variability were computed as the standard deviation of the residual CoP trajectory (i.e., CoP variability at frequencies other than the stimulus frequency) and its derivative, respectively, after subtracting the CoP trajectory corresponding to the visual stimulus frequency. Higher variability indicates lower postural stability (Jeka et al., 2000).

Video-based analyses were used to examine the eye movements performance. Areas of Interest (AOIs) relative to the target location (center, right, and left) were determined. AOIs are two-dimensional (2-D) regions defined in the participant's viewing plane and where fixation patterns are identified. Fixation onset was defined as two times the point of gaze standard deviation (95% confidence interval) less than one degree of visual angle (horizontal and vertical) over 100 ms (seven data points); fixation offset was defined as three data samples deviated from the initial fixation value by more than one degree of visual angle (horizontal and vertical). To examine the gaze performance, the following variables were calculated: (a) number of fixations in the AOIs in each trial; (b) mean fixation duration throughout each trial; (c) Eye response time, i.e., time interval between the appearance of the target to the right or left sides and the first fixation of the participant on the respective target; and (d) Saccades fixation error, i.e., some numbers of fixations directed to other locations of the visual scene than the AOI relative to the appearance of the target.

For the visual memorization task, we examined the task performance of the experimental group in scoring the number of errors when the participant reported incorrectly the total number of times the number 6 appeared throughout each trial.

2.5 Statistical Analysis

T-tests were performed to examine differences between groups for age, body mass, and height. Two-way mixed ANOVAs were performed to verify the influence of simultaneous tasks on the CoP displacements, with groups (control group and experimental groups) and room amplitude conditions (pre-low, high, and post-low conditions) as independent factors. The dependent variable of these analyses was the mean amplitude of CoP displacements in the AP and ML axes. Gain, phase, position, and velocity variability were dependent variables of other two-way mixed ANOVAs (2 groups x 3 conditions) to verify the relationship between room movement and CoP displacements. Additional two-way mixed ANOVAs were performed to examine possible differences in the gaze performance between groups and within room amplitude conditions, with the number of fixations, mean fixation duration, eye movement time, and saccades fixation error as dependent variables. Freidman’s non-parametric test was performed to verify differences in the number of errors of the memorization task during the room amplitude conditions (pre-low, high, and post-low conditions).

The effect size (η2, partial eta-squared) was calculated for each analysis and classified as small (0.2 or less), medium (0.5), and large (0.8) (Cohen, 1988). The initial α adopted for all analyses was 0.05, and post hoc analyses with Bonferroni adjustments were performed when necessary. The software used was the Statistical Package for Social Science (IBM SPSS Statistics, 20.0, New York, US).

3. RESULTS

3.1 Age and anthropometric measures

There were no significant differences between the control and experimental group regarding the demographic characteristics of age ($t(28) = -0.406$, $p=0.688$), body mass ($t(28) = -0.102$, $p<0.919$), and body height ($t(28) = -0.629$, $p<0.534$).

3.2 Postural Sway

3.2.1 Mean Amplitude of CoP displacements

ANOVA indicated a significant room amplitude effect for the mean amplitude of CoP displacement ($F_{2,56}=22.733$, $p=0.0001$, $\eta 2=0.448$) in the AP axis. Post hoc tests revealed a higher mean amplitude of CoP displacements during high amplitude condition compared to the pre-low ($p<0.001$) and post-low ($p<0.001$) conditions, and higher during pre-low than post-low amplitude condition ($p<0.05$) (Figure 4A). No main group effect ($F_{1,28}=0.110$, $p=0.743$, $\eta 2=0.004$), and no interaction effect between groups and room amplitude conditions were found ($F_{2,56}=0.559$, $p=0.575$, $\eta 2=0.020$). ANOVA indicated no differences in the ML axis in any condition for the mean amplitude ($p>0.05$) (Figure 4B). There was no main group effect ($F_{1,28}=0.099$, $p=0.756$, $\eta 2=0.004$), room amplitude conditions ($F_{2,56}=2.068$, $p=0.136$, $\eta 2=0.069$), and no interaction effect between groups and room amplitude conditions ($F_{2,56}=0.031$, $p=0.970$, $\eta 2=0.001$) for the amplitude of CoP displacements in the ML axis.

[INSERT FIGURE 4]

3.3 Influence of room motion on CoP displacements

3.3.1 Gain and Phase

ANOVAs indicated a significant room amplitude condition effect for gain ($F_{2,56}=197.83$, $p<0.0001$, $\eta 2=0.87$). Post hoc tests revealed a lower gain during the high amplitude condition compared to pre-low ($p<0.001$) and post-low ($p<0.001$) conditions and lower during post-low compared to pre-low amplitude condition ($p<0.001$) (Figure 5A). There was no main effect of group ($F_{1,28}=0.391$, $p=0{,}537$, $\eta 2=0.014$) and no interaction effect ($F_{2,56}=0.161$, $p=0{,}852$, $\eta 2=0.006$) for gain. No differences were found between groups and room amplitude conditions ($F_{1,28}=0.129$, $p=0.723$, $\eta 2=0.005$; $F_{2,56}=0.411$, $p=0.665$, $\eta 2=0.014$) and interactions ($F_{2,56}=0.002$, $p=0.998$, $\eta 2=0.001$) for phase (Figure 5B).

3.3.2 Position and Velocity Variability

ANOVA showed a room amplitude condition effect for position variability ($F_{2,56}=20.197$, $p=0.001$, $\eta 2=0.419$) and velocity variability ($F_{2,56}=50.145$, $p=0.0001$, $\eta 2=0.642$). Post hoc tests revealed higher position and velocity variability during high amplitude condition compared to pre-low ($p<0.001$ for both analyses) and post-low ($p<0.001$ for both analyses) conditions (Figure 5 C and D). No main effect of group (position variability – $F_{1,28}=0.051$, $p=0.823$, $\eta 2=0.002$; velocity variability – $F_{1,28}=1.172$, $p=0.288$, $\eta 2=0.040$) and no interaction effect between groups and room amplitude conditions were found (position variability – $F_{2,56}=0.338$, $p=0.715$, $\eta 2=0.012$; velocity variability – $F_{2,56}=0.213$, $p=0.808$, $\eta 2=0.008$).

[INSERT FIGURE 5]

3.4 Gaze Performance

3.*4.1 Number of fixations, Mean fixation duration, Eye response Time and Saccades fixation error*

Table 1 shows the gaze performance of each group in the room amplitude conditions and the number of errors in the memorization task for the experimental group. ANOVAs showed no main effect of group (number of fixations – $F_{1.28}$=0.014, p=0.908, η2=0.001; mean fixation duration – $F_{1,28}$=0.158, p=0.694 η2=0.006; eye response time – $F_{1,28}$=0.022, p=0.882, η2=0.001; saccades fixation error - $F_{1,28}$=2.394, p=0.133, η2=0.079), room amplitude conditions (number of fixations – $F_{2,56}$=0.082, p=0.921, η2=0.003; mean fixation duration - $F_{2,56}$=0.200, p=0.819, η2=0.007; eye response time - $F_{2,56}$=1.684, p=0.195, η2=0.057; saccades fixation error - $F_{2,56}$=1.314, p=0.277, η2=0.045) and no interaction effect (number of fixations - $F_{2,56}$=0.416, p=0.662, η2=0.015; mean fixation duration - $F_{2,56}$=0.231, p=0.794, η2=0.008; eye response time- $F_{2,56}$=1.650, p=0.201, η2=0.056, saccades fixation error - $F_{2,56}$=1.074, p=0.349, η2=0.037).

[INSERT TABLE 1]

3.5 Memorization Task

3.4.1 Number of errors

Freidman's test revealed no differences in memorization task performance in any condition for the experimental group [$X^2(2) = 0.40$; $p>0.05$].

4. DISCUSSION

We investigated whether the adaptation of postural control to perform saccadic tasks could still be functionally adjusted in challenging conditions when adding a memorization task and a perturbing visual environment. The results showed no differences between groups in the coupling between room motion and CoP displacements and gaze performance during the perturbed saccadic eye movement task. Also, there were no differences in gaze performance between room amplitude conditions in any group. We expected that the memorization task and the perturbing visual environment would worsen postural stability, as shown by previous studies (e.g., Tixier et al. 2021; Aguiar et al. 2014). However, our results did not confirm our hypotheses. These results thus showed how strong postural control is under saccadic eye movements as postural sway was not deteriorated by any or both perturbations.

Initially, we estimated our sample size and found that we needed no more than 28 participants to find significant differences in our combined tasks. We recruited 30 participants, and our analyses did not show any significant main effect of the memorization task on postural control in low-amplitude and high-amplitude room motions. Therefore, our results indicate that postural control is robustly adjusted to perform saccadic tasks, so adjusted that it is not destabilized in adding a concurrent visual memory task to a perturbing visual environment. In our study, it means that the CNS was still able to adapt postural control to changes in the amplitude of the room motion (Carver et al., 2006; Oie et al., 2005) to perform and succeed in both the saccadic and memorizing tasks. Although it held in our experimental condition, it is cautious to consider that similar behavior may not occur in other more perturbing conditions.

Our methodology was relevant to challenge postural control. The room motion in the high amplitude condition modified postural control leading to a decrease in the influence of the room motion on the CoP displacements and an increase in overall CoP sway. Our results indicated an increase in the mean amplitude of CoP displacements during the high amplitude condition. We also found changes in the sensorimotor coupling revealed by fewer postural responses at the frequency of the room motion (0.2 Hz) (i.e., higher position and velocity variability). Hence, as there was no main effect of the simultaneous memorizing task on CoP sway, we can highlight the effectiveness of the eye-posture relationship in our study. These results corroborate recent studies that suggested that attentional demands increase to perform precise visual tasks but do not overload even more when adding another task, either a counting task (Bonnet et al., 2019) or a pointing task (Bonnet et al., 2021). We speculate that the same phenomenon may have existed in our study, thus canceling the potential negative impact of the dual/triple task.

Based on our methodology and results, we suggest that the postural control dynamic was modified to perform and succeed in the saccadic task. Goal-directed postural control to perform the saccadic task was so efficient that any perturbation caused by the memorization task was not able to overload the attentional resources involved in the functional interaction between postural and gaze control. In our study, postural control was functionally adjusted to face both the moving room and the simultaneous task when performing the saccades task.

Regarding gaze performance, there was no memorization task effect on the eye response time during the perturbed saccades in the high-amplitude condition. Therefore, unexpectedly, the increase in CoP mean amplitude due to the high-amplitude condition of the moving room did not lead to any longer eye response time. It means that strong and functional relationship between saccadic eye movements and CoP displacements was not altered by abrupt visual perturbations, even when postural sway was increased. Hence, it suggests that the CNS of young adults is flexible to optimize gaze performance in various environmental conditions. This flexible adaptation of postural control and gaze shifts to succeed in challenging precise visual tasks is consistent with the synergic model of postural control (Bonnet et al., 2019; Bonnet & Baudry, 2016b).

On the one hand, the synergic model assumes that the CNS adjusts postural sway to achieve the goals and specificities of the visual task according to its demands. The greater the difficulty of postural and visual tasks, the greater the cognitive involvement to succeed in both tasks (Bonnet & Baudry, 2016a). On the other hand, the dualistic cognitive models assume that an increased cognitive workload would overwhelm the limited CNS resources, leading to a deterioration in the performance of one or more tasks (postural, visual, and memorization tasks). Based on our experimental conditions, our results seem to support an adaptive interaction between cognition, oculomotor behavior, and postural control and therefore are in line with the synergistic model. In conclusion, young adults seem to be flexible in optimizing their postural control to succeed in multiple tasks even under perturbation.

Our study has some limitations. The first limitation is that we did not use a validated secondary task with various difficulty levels (e.g., N-back task) to challenge the eye-posture relation even more. Despite this, from our experimental set-up, our results support that the cognitive task and the room motion do not affect the postural stabilization to perform saccadic eye movements. A second limitation is that we did not measure other body segments, such as trunk sway and head sway, which could bring a complete description of the effects of the cognitive task on overall postural control. A third limitation might be related to the cut-off frequency of 4 Hz for low-pass filtering of our COP data. A cut-off frequency of approximately 13 Hz has been suggested as the standardized parameter to provide reliable COP data (Koltermann et al., 2018). However, the cut-off frequencies of 4-5 Hz have been used in other studies employing the moving room paradigm, and it was confirmed in our data after we performed residual analysis, minimizing any possible issue related to data filtering.

For clinical applications, future studies should examine whether and to what extent a concurrent cognitive task might affect the postural control adaptation to perform visual tasks in people with cognitive decline and balance problems (e.g., older people and patients with neurodegenerative diseases). Deterioration in the functional relation between postural and oculomotor control could lead to an increased risk of falls in such populations, as similarly suggested by the synergic model of postural control (Bonnet & Baudry, 2016a).

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Table 1. Mean (± standard deviation) of number of fixations, mean fixations duration, saccade reaction time, saccadic fixation error and visual memorization task scores of both groups (control and experimental) during room amplitude conditions (pre-low amplitude, high amplitude and post-low amplitude).

Variables	Groups	Pre-low	High	Post-low
Number of fixations	*Control*	115.80 (±20.66)	114.53 (±21.44)	116.40 (±21.44)
	Experimental	115.2 (±22.19)	117.93 (±28.66)	116.40 (±23.03)
Mean fixation duration (s)	*Control*	0.45 (±0.11)	0.46 (±0.11)	0.45 (±0.09)
	Experimental	0.44 (±0.11)	0.44 (±0.12)	0.44 (±0.10)
Eye response time (s)	*Control*	0.23 (±0.03)	0.23 (±0.03)	0.21 (±0.03)
	Experimental	0.24 (±0.07)	0.22 (±0.03)	0.23 (±0.04)
Saccades Fixation Error (units)	*Control*	0.67 (±1.05)	0.46 (±0.64)	0.53 (±0.83)
	Experimental	0.87 (±1.13)	1.13 (±1.46)	1.27 (±1.39)
Number of individual errors of the memorization task (units - %)*	*Experimental*	3 (20%)	4 (26.6%)	4 (26.6%)

*Variable computed only for the experimental group.

Figure 1. Experimental setup with a participant inside the moving room, standing on a force plate using the eye tracking device while performing the saccadic visual task.

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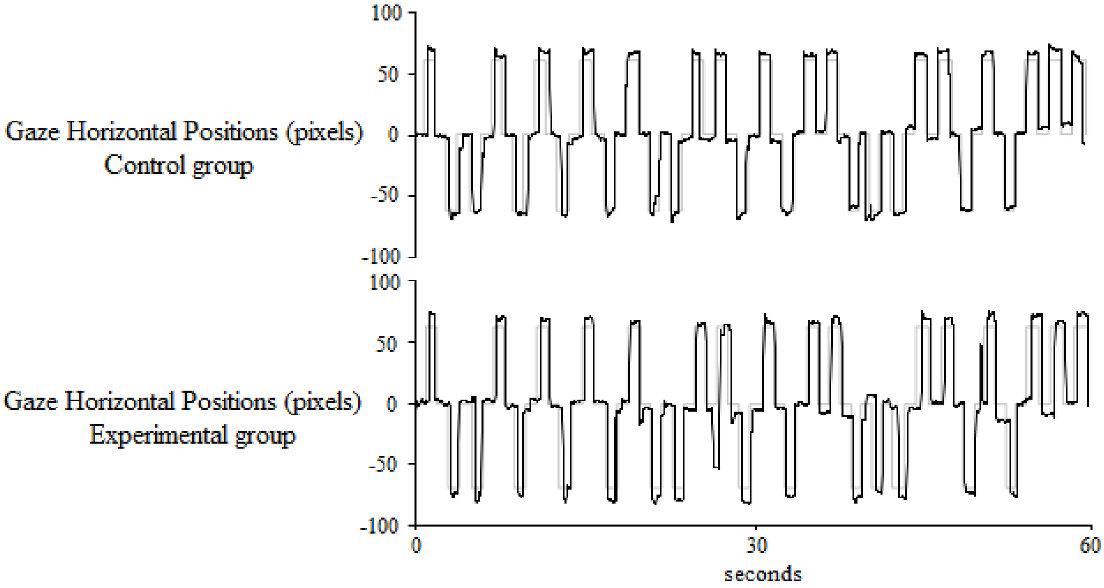

Figure 2. Exemplars of time series of gaze horizontal position (dark line) with time series of the target position (gray line) from one participant of control group (top panel) and one participant of experimental group (bottom panel) during the saccadic task.

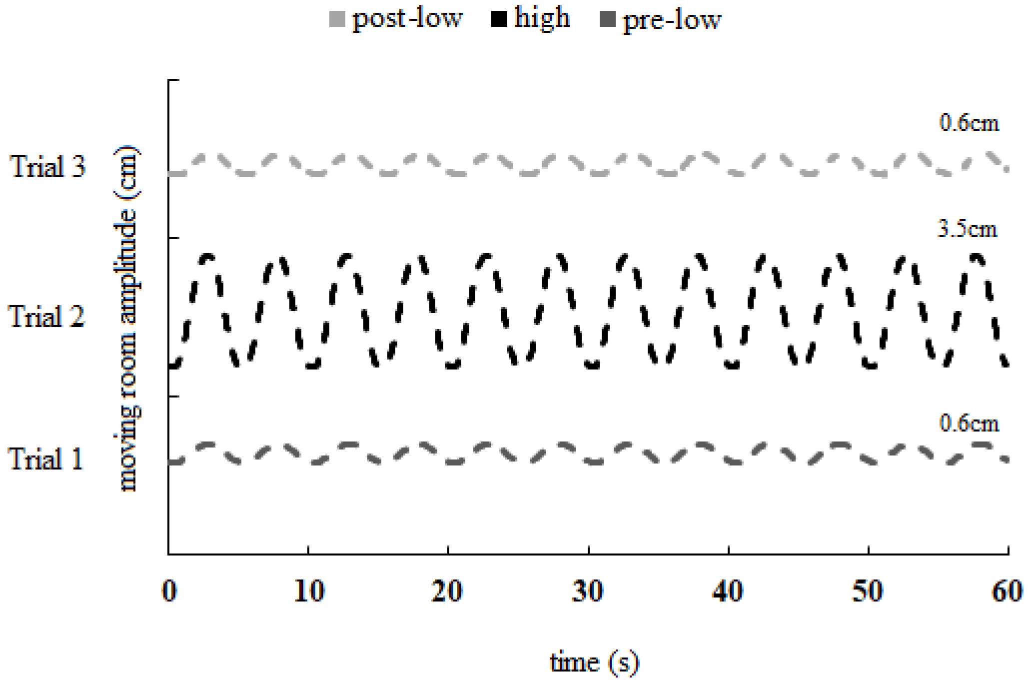

Figure 3. Exemplars of room displacement on each trial condition. The dark gray line corresponds to the first trial (pre-low amplitude condition), the black line corresponds to the second trial (high amplitude condition) and the light gray line represents the third trial (post-low amplitude condition).

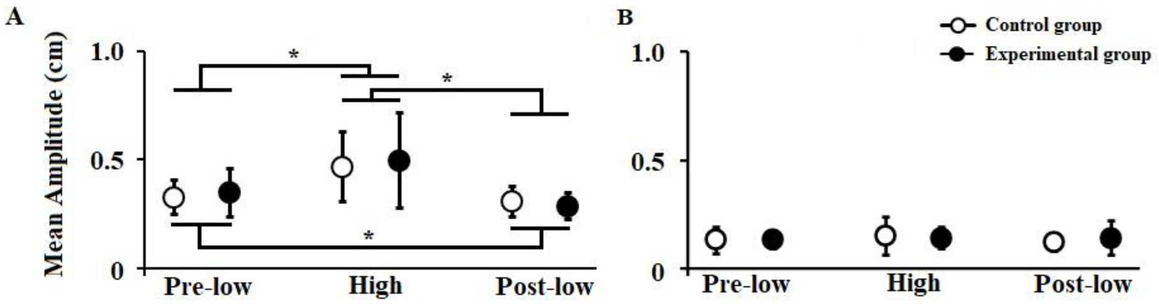

Figure 4. Mean and standard deviation values of mean amplitude of CoP displacements of both groups (control and experimental groups), in the anterior-posterior – AP (painel A) and medial-lateral – ML (painel B) directions, during room amplitude conditions (pre-low amplitude, high amplitude and post-low amplitude). * Main effect of room amplitude condition.

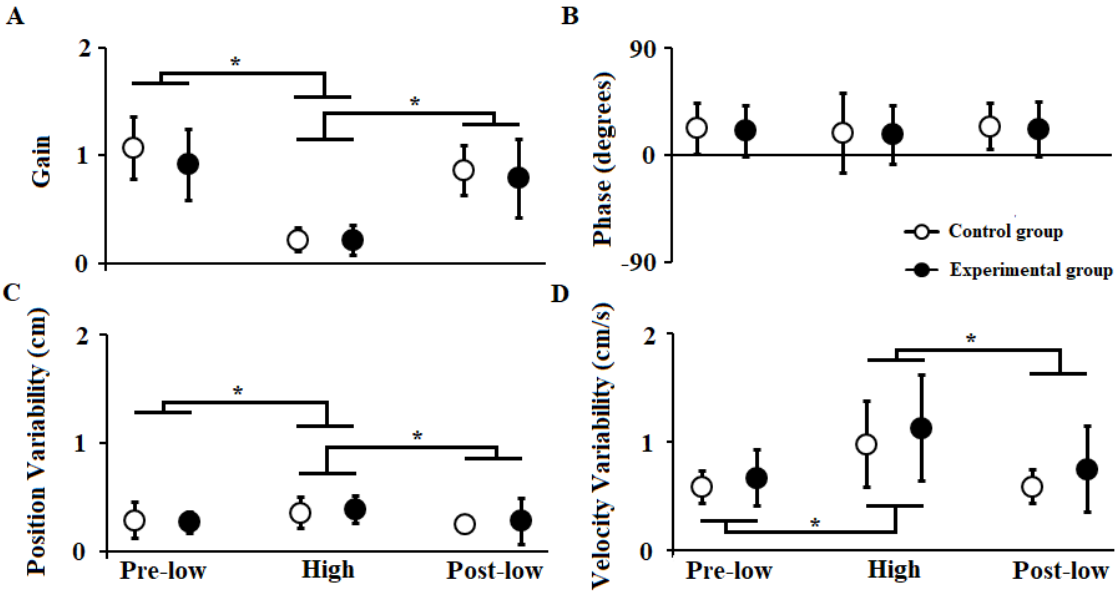

Figure 5. Mean and standard deviation values of gain (A), phase (B), position variability (C) and velocity variability (D) of both groups (control and experimental groups) during the room amplitude conditions (prelow amplitude, high amplitude and post-low amplitude). * Main effect of room amplitude condition.