Cognitive–motor interference revisited: Insights from visual manipulations during standing

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Absract

Postural control during quiet standing is a highly adaptive process that emerges from the continuous interaction between sensory information, motor coordination, and cognitive demands. Dual-task paradigms have traditionally interpreted cognitive–motor interference as competition between independent systems for limited resources. However, alternative dynamical perspectives suggest that posture, perception, and cognition form an integrated coordination structure which is adapted to task and environmental constraints. The present study examined how engaging working memory modulates postural control and cognitive performance under different visual environments. Twenty-seven healthy young adults performed a visual 2-back task while standing in a stationary room or in a moving room oscillating at 0.2 Hz and 0.5 Hz. Postural sway was quantified using center-of-pressure (COP) measures, and visuomotor coupling was assessed through gain, phase, and position variability analyses. Cognitive performance was evaluated using reaction time and task accuracy. Repeated-measures ANOVAs and linear mixed-effects models were used for statistical analysis. Postural sway was reduced across all visual conditions by means of increasing cognitive engagement. Visual perturbation increased visuomotor coupling, particularly at 0.5 Hz, and this effect was amplified during the cognitive task condition. Behavioral results revealed a dissociation between accuracy and reaction time: accuracy remained largely stable, whereas mixed-effects models revealed a context-dependent association between postural sway and reaction time only under the most demanding visual condition. These findings indicate that cognitive–motor interactions are not linear and competitive but emerge selectively as the perception–action system reorganizes to meet environmental demands. Postural sway should therefore be understood as a functional component of behavior, whose role depends on context rather than variability to be minimized.

Introduction

The study of postural control has long served as a window into the organization of perception and action in humans. Although quiet standing might appear as a static and automatic process, it is in fact a highly adaptive behavior that emerges from the ongoing integration of sensory information, motor coordination, and cognitive regulation (Horak, McPherson, 1996; Nashner & McCollum, 1985; Huxhold *et al.*, 2006). When individuals stand upright, they continuously update their body orientation relative to the environment. This process depends not only on vestibular and somatosensory inputs but also on the structure of visual information available in the surrounding scene (Peterka, 2002; Stoffregen & Riccio, 1988; Polastri *et al.*, 2012; Assländer & Peterka, 2014). At the same time, higher-level cognitive operations, such as maintaining information in working memory or engaging executive monitoring, can influence how sensory information is selected, weighted, and used to guide postural behavior (Freitas, Barela 2004; Mitra e Fraizer, 2004; Fraizer, Mitra, 2008; Rougier & Bonnet, 2016; Bonnet & Baudry, 2016a; 2016b).

Dual-task paradigms became a central tool for investigating cognitive–motor interference. By requiring individuals to maintain balance while simultaneously engaging in a cognitive task, these paradigms showed that cognitive activity can either destabilize or reorganize postural control, depending on task demands and sensory context (Woollacott & Shumway-Cook, 2002; Huxhold *et al.*, 2006; Fraizer & Mitra, 2008; Belizario Brito *et al.*, 2023). Despite decades of research, this interaction continues to challenge our understanding of the mechanisms linking cognition and postural control (Fraizer & Mitra, 2008; Yogev-Seligmann *et al.*, 2008). Some studies have shown that posture is not merely a background condition for action but instead an active component of perception–action coupling, continuously adapting to what the task requires and to the information available in the environment. For example, in Bonnet, *et al.* (2024), healthy young adults stood freely while performing visual search tasks (modified Stroop task) designed to engage selective attention and goal achievement. Task difficulty was manipulated by systematically increasing cognitive conflict:

in the incongruent condition, word meaning and ink color conflicted (e.g. the word green colored in another color such as yellow, black, red…), requiring inhibition of automatic reading; and in the reversed-incongruent condition, participants had to follow an inverted rule, responding to word meaning instead of color, which further increased executive demands (e.g. if the word green was colored in pink, the participant had to imagine that he was seen the word pink colored in green). Participants performed the tasks under four body configurations: standing against a wall with full trunk support, standing freely with a wide stance, standing freely with a standard stance, and standing freely with a narrow stance. No external perturbations were applied to any condition. The results revealed that greater postural sway was positively associated with higher visual task performance, particularly when participants stood freely. It suggested that postural variability facilitated cognitive performance (Bonnet *et al.*, 2024).

Hence, posture could be viewed as an active component of perception–action coupling, continuously adapting to what the task requires and to the information available in the environment. This idea aligns closely with dynamical systems approaches, which propose that coordinated patterns of behavior emerge from interactions among multiple degrees of freedom (Kelso, 1995; Latash, 2008). In the present chapter, we continued revisiting the concept of cognitive–motor interference from a perception–action perspective, emphasizing the central role of environmental information and treating cognitive and sensorimotor processes as integrated components of a unified coordination system. In the present study, young adults performed a 2-back working memory task while standing quietly under different visual conditions, including a stable environment and a moving-room frequency manipulation that perturbs optic flow (see Lee, Lishman, 1975, Dijskstra *et al.*, 1994; for more details). This combination allowed us to examine how cognitive engagement reorganizes postural control when visual information is experimentally altered. Specifically, this study aimed to understand how engaging working memory influences the organization of postural control under different visual conditions, and whether interactions between cognition and posture reflect simple interference or an adaptive reorganization of postural control within a perception–action framework. We hypothesized that under visual perturbation, postural sway at different frequencies of the moving room would be systematically associated with cognitive performance, indicating functional coupling between postural dynamics and task execution.

Methods

Participants

Twenty-seven young adult university students participated in the study (mean age = 22.2 ± 2.29 years; mean body mass = 66.8 ± 12.3 kg; mean height = 1.68 ± 0.06 m). Inclusion criteria were: age between 18 and 35 years; normal or corrected-to-normal visual acuity (Snellen 20/20–20/25); and cognitive test scores within the normal range (scores between 27 and 30). Exclusion criteria included musculoskeletal (e.g., fibromyalgia, injuries), physical (e.g., prostheses), and sensory impairments (e.g., dizziness, vertigo, severe visual problems, among others) that could compromise performance on the proposed tests. Participants were informed about the experimental procedures and, after agreeing to participate, signed a written informed consent form approved by the Ethics Committee of the School of Sciences – UNESP, Bauru Campus (CAAE: #04406818.0.0000.5398).

Procedures

Data collection was conducted at the Laboratory of Information, Vision, and Action (LIVIA) at UNESP – Bauru Campus. Initially, participants completed a questionnaire to gather qualitative information regarding their profile and medical and family history. Subsequently, the Mini-Mental State Examination (MMSE), a clinical test used to assess cognitive status, was administered. Body mass, height, and visual acuity (Snellen test) were then measured.

Participants were positioned in an upright stance on a force platform located at the center of a moving room. The force platform (AMTI – AccuGait) consisted of a plate with four electrical sensors that measure horizontal and vertical force components (Fx, Fy, and Fz) and the corresponding moments (Mx, My, and Mz), which were subsequently used to calculate center of pressure (COP) displacements. The moving room was used to manipulate participants' optical flow and increase body sway corresponding to the visual stimulus parameters, without prior knowledge of this manipulation. The apparatus consisted of an aluminum structure measuring 2.1 × 2.1 × 2.1 m (height, width, and length). Its inner walls were painted white with alternating black vertical stripes to increase environmental contrast. The structure was mounted on silicone wheels positioned on rails fixed to the floor, allowing continuous forward and backward movement independently of the floor. Movements were generated by a controller (Parker Compumotor – Model 6k8) and a stepper motor (Model PL06) attached to the back wall of the room. Movement parameters (amplitude, velocity, and frequency) were controlled by specific computer programs (Compumotor – Motion Architect) written in a programming language. Room displacement was measured by a sensor mounted on the side wall of the room, which is part of a magnetic motion analysis system consisting of a receiver, a transmitter, and a control unit (Flock of Birds Magnetic System). A multimedia projector (EPSON PowerLite W6) mounted on the ceiling of the room was used to project the visual task onto the front wall. The sampling frequency of all equipment was 60 Hz. Figure 1 illustrates the experimental setup of the study.

Participants were instructed to stand upright with their feet parallel, remain as still as possible, keep their arms relaxed alongside the body, and hold a mouse in the dominant hand (100% of participants used the right hand), positioned parallel to the thigh. Participants were instructed to use the mouse without touching any part of their body. Two cognitive task conditions were performed: with and without a visual 2-back task, named Task (T) and No Task (NT) condition, respectively; under three visual environmental conditions: a stationary environment (ST), in which the room remained stationary, and a moving-room environment, in which the room oscillated at frequencies of 0.2 Hz and 0.5 Hz, with a constant velocity of 0.75 cm/s. The higher frequency was used to increase the demands on postural control.

Participants performed two trials in the stationary room condition, two trials with the moving room at 0.2 Hz, and two trials with the moving room at 0.5 Hz, resulting in six trials in the Task condition and six trials in the No Task condition, for a total of 12 trials. Each trial lasted 60 seconds. In the first two and the last two trials (Task and No Task conditions), the room remained stationary. Trials order was counterbalanced and randomized to avoid order effects. Between trials, participants were given a rest period of approximately 60 seconds to minimize physical and/or mental fatigue.

Figure 1. Experimental set-up with an adult standing on the force plate, inside the moving room.

The 2-back task consisted of viewing a sequence of numbers projected onto the front wall of the room, directly in front of the participant, at eye level. Whenever the participant identified that the number presented on the screen was the same as the number presented two numbers earlier, they were instructed to press the left mouse button as quickly as possible. If this congruency did not occur, participants were instructed to memorize the number without pressing the mouse button and wait for the next number to appear on the screen.

The task began with a blank screen displayed for 1.2 milliseconds (ms), followed by the appearance of a white circle that remained at the center of the screen for 750 ms Participants were instructed to fixate on this target until it disappeared, after which a number appeared on the screen and remained visible for 909 ms. After the number disappeared, the sequence restarted and was repeated continuously over 60 seconds, resulting in a sequence of 21 numbers. This task required sustained attention and working memory and was characterized by a moderate level of difficulty. Figure 2 illustrates the experimental design of the study.

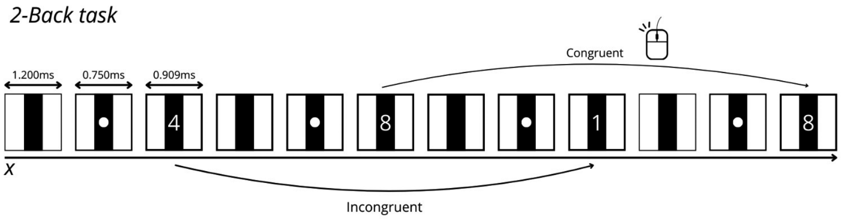

Figure 2. Experimental design showing the sequence of numbers and the duration of each stimulus.

Both the numbers and the circle had a diameter of 3 cm. The white circle preceding the appearance of the numbers was used to ensure that all participants were fixating on the center of the screen at the moment the numbers appeared and could respond as quickly as possible to the presence or absence of congruency. This task was programmed using PsychoPy software in the Python programming language. Six different programs were created, one for each stationary and moving-room trial, to avoid task learning effects. Before data collection began, participants received standardized instructions regarding the 2-back task and completed a familiarization session with the experimental procedures to ensure full understanding. However, participants were not informed about the visual manipulation provided by the moving room so as not to influence the behavior to be observed (Freitas & Barela, 2004). The onset of the cognitive task was synchronized with the other equipment in each trial by means of an external trigger and a 2.4 GHz wireless keyboard.

Data analysis

Data obtained from the force plate and the magnetic sensor were processed and analyzed using MATLAB software (2023). Initially, the data were filtered using a second-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. To quantify the variability of COP displacements across experimental conditions, mean amplitude was calculated from the standard deviation of the COP trajectory after subtracting the mean COP position within each trial, along the anteroposterior (AP) axis (the direction of room movement).

To quantify the coupling between COP displacements and the room movements (visual stimulus), a Frequency Response Function (FRF) analysis was performed. This function consisted of dividing the Fourier transforms of the COP trajectory by the Fourier transforms of the room trajectory at the same stimulus frequency, yielding a complex-valued function for each trial. This analysis was computed on a cycle-by-cycle basis, separately for each visual stimulus frequency (0.2 Hz and 0.5 Hz). From this analysis, the following variables were calculated: (a) Gain – obtained from the magnitude (absolute value) of the complex FRF values. This variable indicates the coupling between the amplitude of room movement and the amplitude of COP displacement in the AP direction (direction of room movement). Gain values close to 1 indicate that the amplitude of COP displacement matched the amplitude of room movement; (b) Phase – obtained from the argument of the complex FRF values, converted from radians to degrees. This variable indicates the temporal relationship between the visual stimulus (room movement) and COP displacement. Positive and negative values indicate that COP displacements led or lagged behind the room movements, respectively.

In addition, COP position variability was calculated for the trials in which participants were exposed to room movement. This variable differed from the overall amplitude, as it represented the variability of COP displacements under the effect of visual manipulation, reflecting how stable the coupling between COP displacements and the visual stimulus provided by the moving room was. To calculate this variable, the standard deviation of the residual COP trajectory was obtained after removing the signal component corresponding to each room movement frequency. Therefore, this variable represented the variability of COP displacements at frequencies different from those of the room movements adopted in this study (0.2 Hz and 0.5 Hz).

Cognitive variables

Data generated by the PsychoPy software were stored in ASCII format. To quantify cognitive task performance (accuracy and processing time) across the different experimental conditions, the number of correct responses and reaction time (RT) were computed. A correct response was defined as pressing the mouse button when the presented number matched the number shown earlier (congruency). The total number of correct responses per trial was computed for each participant. These values were normalized by dividing the number of correct responses obtained by the total number of possible correct responses for each trial and multiplying by 100. Mean values for each condition were then extracted for each participant. Reaction time (RT) was defined as the time interval between the appearance of the number on the screen and the mouse button press during the trial. RT was computed only for correct responses in the number sequence. Then, mean RT values were extracted for each trial and condition for each participant.

Statistical analysis

Shapiro–Wilk tests were conducted to assess data normality, and data were transformed when necessary. To investigate the effect of the cognitive task on posture under different visual environment manipulations, a two-way repeated-measures ANOVA (2 × 3) was performed with task (Task and No Task) and visual environment (stationary, 0.2 Hz, and 0.5 Hz) as within-subject factors. The dependent variable was the mean amplitude of COP displacement in the anteroposterior (AP) direction. Another set of two-way repeated-measures ANOVAs (2 × 2) was conducted to examine the effects of task and room movement frequency (0.2 Hz and 0.5 Hz) on visuomotor coupling. The dependent variables were gain and phase between COP displacements and room movement, as well as COP position variability. To examine participants' performance on the cognitive task, a one-way repeated-measures ANOVA was conducted with visual environment (stationary, 0.2 Hz, and 0.5 Hz) as the within-subject factor for the reaction time variable. In addition, post hoc tests with Bonferroni adjustments were performed when necessary. A nonparametric Wilcoxon test was used to examine differences between environmental conditions for the percentage of correct responses.

Finally, a linear mixed-effects model was used to examine the association between task performance and postural measures across experimental conditions. Reaction time was entered as the dependent variable, condition (Stationary, 0,2 Hz, and 0,5 Hz frequencies) was treated as a within-subject factor, and the postural variable (i.e., mean amplitude in Task condition) was included as a continuous covariate. Random intercepts were specified for participants, and an autoregressive covariance structure (AR(1)) was used to account for within-subject dependencies. Models were estimated using restricted maximum likelihood (REML). A second linear mixed-effects model was conducted to examine whether postural measures were associated with task accuracy. The percentage of correct responses was entered as the dependent variable, condition as a within-subject factor, and mean amplitude of COP displacements in the Task condition as a continuous covariate. The same random and covariance structures were applied as in the reaction time analysis. All statistical analyses were conducted using SPSS software (version 21.0), and the alpha level was set at 0.05.

Results

Mean amplitude of COP displacements

The results showed a main effect of task ($F_{(1,36)} = 34.27$, $p < .0001$, $\eta^2 = .546$) and a main effect of visual environment ($F_{(2,52)} = 15.50$, $p < .0001$, $\eta^2 = .374$), but no interaction between task and visual environment ($p > .05$) for the mean amplitude of COP displacement. Post hoc tests indicated lower COP displacement variability in the anteroposterior (AP) direction in the Task condition ($p < .0001$) and lower variability in the stationary room condition compared with the moving-room condition at frequencies of 0.2 Hz ($p < .0001$) and 0.5 Hz ($p < .003$). Figure 3 (A-D) shows the results for the mean amplitude of COP displacement in the AP direction (Figure 3A), in the Task and No

Task conditions, under the stationary room condition, and at room movement frequencies of 0.2 and 0.5 Hz.

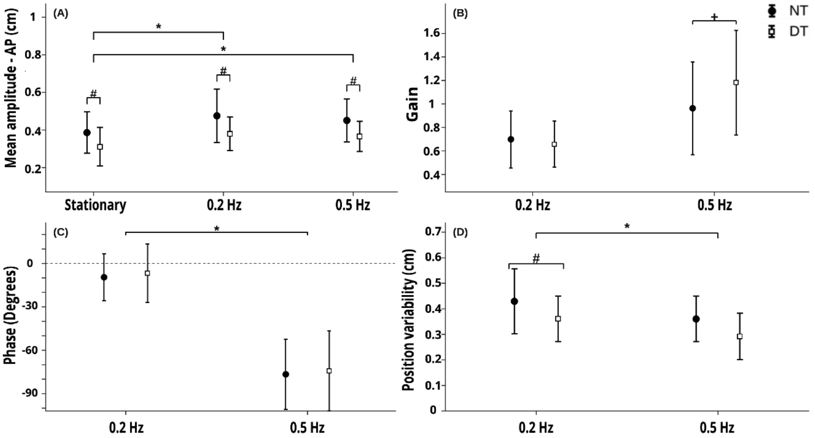

Figure 3. Mean values and standard deviations of the mean amplitude of COP displacement (A), gain (B) and phase (C) between COP displacements and room movement, and COP position variability (D), under the stationary room condition, the moving-room condition at 0.2 Hz, and the moving-room condition at 0.5 Hz, in Task (T) and No Task (NT) conditions. The symbol * indicates a main effect of environment/frequency, # indicates a main effect of task, and + indicates an environment × task interaction.

Coupling between COP displacements and room movements

The results indicated that participants' COP displacements were induced by the movements of the room, with frequency peaks corresponding to the room movement frequency. Figures 4 and 5 present examples of time-series and spectral data of COP displacement and room movement throughout a trial from one participant, in Task and No Task conditions, at room movement frequencies of 0.2 and 0.5 Hz.

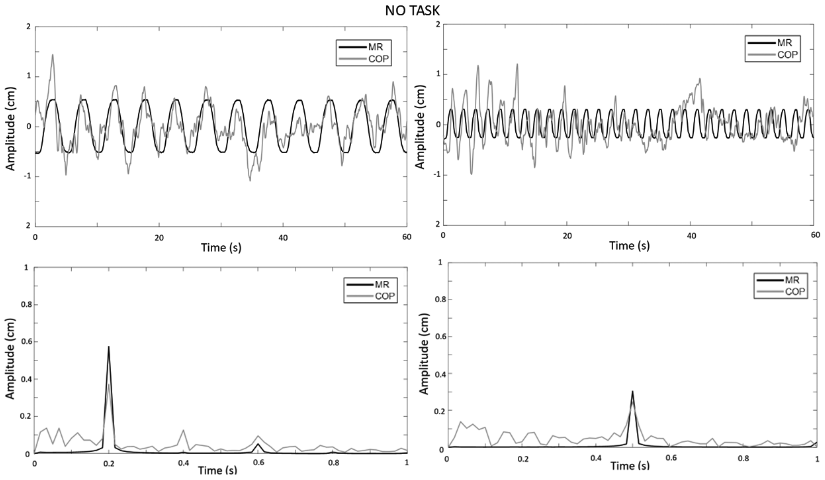

Figure 4. Examples of time series of COP displacements (top panels) and amplitude spectra of COP displacements and moving-room motion (bottom panels) at frequencies of 0.2 Hz (left panels) and 0.5 Hz (right panels), in the anteroposterior (AP) direction, during the No-task condition. The black line represents the moving room (MR), and the gray line represents COP displacements.

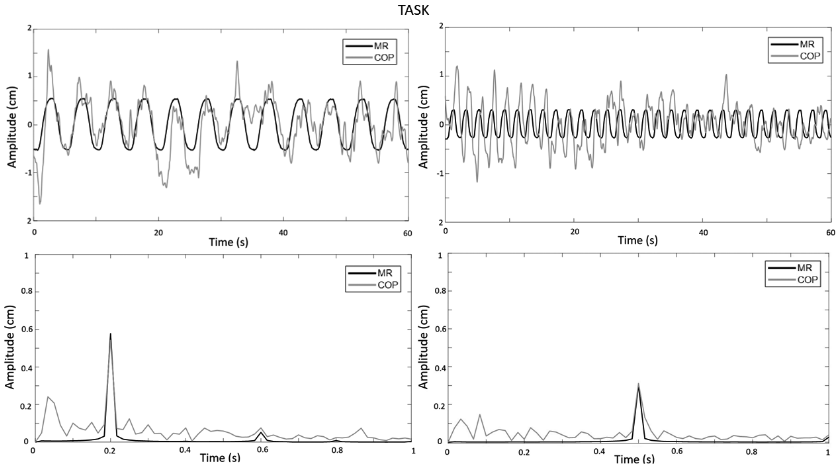

Figure 5. Examples of time series of COP displacements (top panels) and amplitude spectra of COP displacements and moving-room motion (bottom panels) at frequencies of 0.2 Hz (left panels) and 0.5 Hz (right panels), in the anteroposterior (AP) direction, during the Task condition. The black line represents the moving room (MR), and the gray line represents COP displacements.

The ANOVA indicated a significant interaction between task and room frequency for gain (F($_{1,26)}$ = 12.91, $p < .001$, $\eta^2 = .332$), as well as a main effect of task (F($_{1,26)}$ = 6.61, $p < .002$, $\eta^2 = .192$) and a main effect of frequency ($F_{(1,26)} = 51.53$, $p < .0001$, $\eta^2 = .665$). Post hoc tests for the main effects indicated higher gain values in the Task condition ($p < .02$) and at the 0.5 Hz frequency ($p < .0001$). However, the interaction revealed that gain values were significantly higher only during the Task condition at the 0.5 Hz frequency ($p < .0001$) (Figure 3B). For the phase variable, the ANOVA revealed a main effect of frequency ($F_{(1,26)} = 165.66$, $p < .0001$, $\eta^2 = .864$). Post hoc tests indicated negative phase values at the 0.5 Hz frequency, indicating that COP displacements temporally lagged behind room movements at 0.5 Hz compared with 0.2 Hz ($p < .0001$) (Figure 3C). For COP position variability, the ANOVA revealed a main effect of task ($F_{(1,26)} = 37.04$, $p < .0001$, $\eta^2 = .588$) and a main effect of room frequency ($F_{(1,26)} = 45.33$, $p < .0001$, $\eta^2 = .636$), but no interaction between task and frequency ($p > 0.05$). Post hoc tests indicated lower values of COP position variability in the Task condition ($p < 0.0001$) compared to the No-Task condition, and at the 0.5 Hz frequency ($p < 0.0001$) compared to 0.2 Hz (Figure 3D).

Cognitive task performance

Regarding performance on the 2-back task, the results showed no differences across the stationary room condition, the moving-room condition at 0.2 Hz, and the moving-room condition at 0.5 Hz for reaction time ($F_{(2,52)} = .089$, $p > 0.05$, $\eta^2 = .003$). With respect to task accuracy, nonparametric Wilcoxon tests indicated a lower percentage of correct responses only in the moving-room condition at 0.5 Hz compared with the stationary room condition ($p < 0.02$).

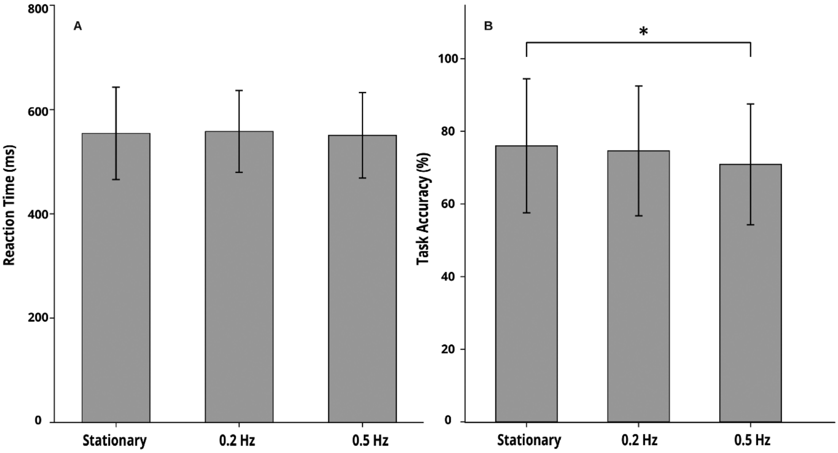

Figure 6. Mean values and standard deviations of the reaction time (A) and percentage of correct responses (task accuracy), under the stationary room condition, the moving-room condition at 0.2 Hz, and the moving-room condition at 0.5 Hz, in the task condition. The symbol * indicates a main effect of environment/ frequency.

Mixed model ANOVA

The mixed model revealed a significant main effect of condition on reaction time ($F_{(2,\ 50.1)} = 4.15$, $p < .03$). A significant interaction between condition and postural measure was also observed ($F_{(2,\ 50.2)} = 3.84$, $p < .03$). Post hoc inspection of the fixed effects indicated no association between postural sway and reaction time in the static condition. In contrast, a significant positive association emerged in the most demanding condition (room motion at 0.5 Hz frequency), with higher mean amplitude values associated with longer reaction times (Figure 7). The mixed model revealed no significant effects of condition ($F_{(2,\ 42.1)} = .67$, $p = .515$), postural sway ($F_{(1,\ 68.5)} < 0.01$, $p = .984$), or their interaction ($F_{(2,\ 42.4)} = 0.44$, $p = .650$) on task accuracy. These results indicate that accuracy remained stable across conditions and was not influenced by postural demands.

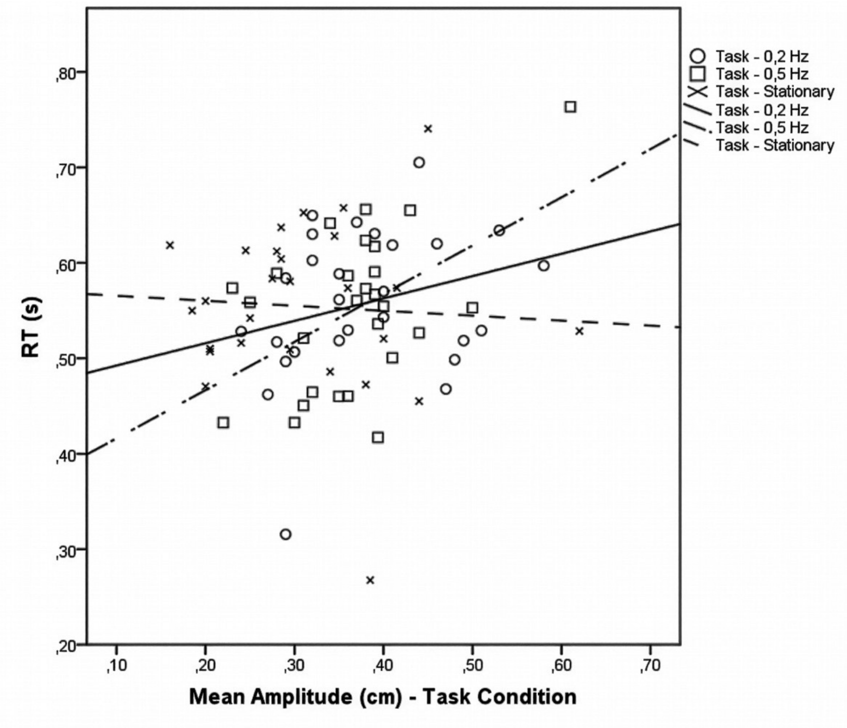

Figure 7. Interaction between the mean amplitude of COP in the task condition and reaction time across experimental conditions. Regression lines are shown separately for each condition. The association between postural sway and reaction time was insignificant in the stationary condition and increased in the more demanding condition, reaching significance in the room movement at 0.5 Hz condition.

Discussion

The present study was design to put forward a perception–action perspective, in questioning the cognitive-motor interference, in examining how engagement in a working memory task reorganizes postural control under different visual environments. Using a combination of repeated-measures approaches and linear mixed-effects modeling, we showed that the relation between cognition and posture depends on context, emerging from the specific informational demands imposed by the task and the environment instead of interacting in a single or strictly competitive manner. The fact that the association between postural sway and reaction time was only observed under the most demanding visual condition (0.5 Hz) indicates that cognitive-postural coupling emerges as a function of task constraints.

Postural reorganization under cognitive engagement

Our results showed a robust main effect of task on COP displacements, with reduced COP variability during the cognitive task across all visual environments. This finding aligns with previous studies showing that cognitive engagement can stabilize posture, often interpreted as a shift toward a more constrained control strategy (Huxhold *et al.*, 2006; Fraizer & Mitra, 2008). It is interesting to note that this stabilization effect occurred regardless of whether visual information was stable or perturbed, which suggests that the cognitive task imposed a general constraint on postural control. Previous experimental studies have consistently shown that engagement in cognitive tasks leads to reduced postural variability, even under altered sensory conditions (Stoffregen *et al.*, 2007; Fraizer & Mitra, 2008). From an ecological perspective, such reduction does not reflect improved stability per se, but rather a functional reorganization of postural degrees of freedom in response to task demands (Newell, 1986; Stergiou *et al.*, 2006). It is consistent with the notion that posture adapts proactively to anticipated task requirements (Stoffregen et al, 2000), and further indicates that postural behavior emerges from the continuous interaction between perceptual, cognitive, and motor processes under varying task and environmental demands.

Visual perturbation and visuomotor coupling

The analyses of visuomotor coupling provide further insight into how postural control adapts when visual information is altered. As the frequency of room movement increased, gain values also increased, indicating that postural sway more closely followed the visual stimulus. This effect was particularly pronounced during the cognitive task, especially at 0.5 Hz. Such an interaction suggests that as visual perturbations become more demanding, participants rely more strongly on visual information to regulate posture, and this reliance is amplified under cognitive load. In parallel, phase analyses revealed systematic temporal lags at the higher frequency, pointing to constraints in the sensorimotor system's ability to track rapidly changing visual input. Together, these findings indicate that postural control under visual perturbation reflects a functional coupling to visual information, which is modulated by both the dynamics of the environment and the cognitive demands of the task (Stoffregen et al, 2000; Genoves *et al.*, 2016; Aguiar *et al.*, 2014).

Cognitive performance: stability of accuracy and selective cost in timing

Behavioral performance on the cognitive task revealed a clear dissociation between accuracy and reaction time. Accuracy remained largely stable across visual conditions, showing only a small reduction at the highest room movement frequency (0.5 Hz). Although this reduction reached statistical significance, it did not appear to have functional relevance, since the participants remained highly accurate even under the most demanding condition. This result may reflect that the system was operating closer to its functional limits, while still maintaining overall task success. Reaction time, in contrast, did not differ across conditions in the repeated-measures analysis, suggesting that average reaction time alone lacks the sensitivity to capture subtle interactions between cognitive processes and postural control. These results suggest that participants prioritized response accuracy even as postural and visual demands increased, while allowing response timing to remain more flexible.

The linear mixed-effects models, however, revealed clear evidence of context-dependent cognitive–motor coupling. When reaction time was examined in relation to postural sway, the analyses showed a significant interaction between task condition and visual environment. No association between the mean amplitude of COP displacement and reaction time was observed in the stationary condition, indicating that under stable sensory conditions, postural control operates largely independently of cognitive timing. In contrast, under the most demanding visual perturbation (0.5 Hz), greater postural sway was associated with longer reaction times, suggesting that posture and cognition became functionally linked when the environment required active sensorimotor regulation.

This pattern cannot be explained by a simple interference account in which postural demands uniformly degrade cognitive performance. Rather, it indicates that cognitive–motor interactions emerge selectively as the perception–action system reorganizes to meet increasing environmental constraints. Importantly, the absence of any association between postural measures and task accuracy in the second mixed-effects model reinforces this interpretation, showing that cognitive–motor interference manifested primarily in the temporal domain of performance, while outcome accuracy remained stable. Such selectivity is difficult to reconcile with capacity-sharing models alone, which would predict more generalized performance costs, but it is well aligned with dynamical approaches emphasizing flexible, context-dependent reorganization of the perception–action system (Kelso, 1995; Newell, 1986; Woollacott & Shumway-Cook, 2002; Mitra & Fraizer, 2004).

Taken together, the results challenge the traditional view that cognitive and motor processes operate as separate systems that compete for limited CNS resources, leading to a deterioration in the performance of one or more tasks (postural, visual, and memory tasks) (Woollacott & Shumway-Cook, 2002). Instead, they are more consistent with the idea that assumes posture, perception, and cognition as components of a flexible coordination structure that adapts to task and environmental constraints (Belizário Brito et al, 2023; Bonnet *et al.*, 2024; Hua et al, 2025). From this perspective, postural sway is no longer viewed as meaningless variability to be minimized, but a functional aspect of behavior that can either support or limit task performance depending on the context.

The present findings extend this perspective by demonstrating that the emergence of posture–cognition coupling depends critically on the informational properties of the environment, particularly the dynamics of visual input. Specifically, higher-frequency visual perturbations appear to push the system toward tighter functional coupling, revealing relationships between postural dynamics and cognitive timing that remain hidden under stable sensory conditions (i.e., a stationary room). This sensitivity to context highlights the need to consider both environmental information and system dynamics when interpreting interactions between cognition and movement.

Limitations and future directions

Despite its contributions, this study has some limitations. First, the sample consisted exclusively of healthy young adults, limiting the generalizability of the findings to older adults, children, or clinical populations, whose perception–action systems may exhibit different coordination dynamics. Second, only a single level of cognitive load (2-back task) was employed, restricting insights into how varying cognitive demands influence postural reorganization. Future studies should incorporate increasing cognitive loads and tasks of different cognitive domains (e.g., spatial, verbal, etc) for different populations.

Conclusion

In conclusion, this study demonstrated that cognitive–motor interactions during standing are best understood as adaptive reorganizations of perception–action systems, rather than as fixed interference effects. Cognitive engagement stabilized posture globally, but under demanding visual conditions, postural dynamics become functionally linked to reaction time, revealing a selective and context-dependent form of interference. These findings underscore the importance of considering environmental information, task demands, and system dynamics when interpreting cognitive–motor interactions in both experimental and applied settings.

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