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Dual task interferes with sensorimotor coupling in postural control

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Abstract

Although the effects of cognitive tasks on postural control have been widely investigated, the influence of cognitive load on sensorimotor coupling in postural control is still being uncovered. The purpose of the present study was to investigate and compare the influence of conscious knowledge, intention, and cognitive load on the relationship between visual information and body sway in postural control in young adults. Sixteen young adults stood upright, as still as possible, inside a moving room under four experimental conditions: the participants remained still without knowing that the room was moving (dynamic condition); the participants were informed about the room's movement (information condition) and asked to resist the room's movement (resisted condition); the participants performed a counting task while resisting the visual influence (dual-task condition). The results showed that the influence of visual manipulation on body sway decreased when the participants were informed about the movement of the room and decreased further after they were asked to resist its movement. However, performing a dual-task led to an increase in visual influence. We conclude that intention plays a role in sensorimotor system functioning in the postural control system to alter its function if required. Nevertheless, such change demands cognitive effort, which limits attentional resources and can compromise performance in secondary tasks. **Keywords:** dual-task, attention, posture, sensorimotor coupling.

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Introduction

To maintain a desired postural orientation, the postural control system fuses sensory cues that come from visual, vestibular, and somatosensory channels to produce appropriate muscle activation. The two behavioral goals of postural control are postural equilibrium and orientation, which strongly depend on a dynamic relationship between sensory information and motor action (Horak & Macpherson, 1996). The involvement of cognition in postural control has been widely investigated. A common approach to clarifying issues related to this matter is the use of an additional task while one maintains a specific postural orientation (i.e., a dual-task paradigm). Different studies have investigated the effects of an additional task, such as

eye movements (Rodrigues, Aguiar, Polastri, Godoi, Moraes, & Barela, 2013; Stoffregen, Bardy, Bonnet, Hove, & Oullier, 2007), reading (Legrand, Bui-Quoc, Dore-Mazars, Lemoine, Gerard, & Bucci, 2012), visual search (Mitra & Fraizer, 2004), counting backward (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002), and memory tasks (Riley, Mitra, Saunders, Kiefer, & Wallot, 2012), on postural control performance. One common suggestion is that the two tasks, a postural task and an additional task, would compete for limited attentional resources, which could affect performance in one or both tasks.

The results observed in such dual-task studies have generally shown an interference effect of the secondary task on postural control performance, leading to the suggestion that a cognitive component or attentional requirements are related to postural control (Shumway-Cook & Woollacott, 2000). However, still unknown is whether this cognitive component is related to the gathering of sensory information from many sources in the environment, production of motor actions, or relationship between sensory information and motor action.

Barela and colleagues (Barela, Dias, Godoi, Viana, & de Freitas, 2011; Freitas Junior & Barela, 2004) argued

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that in maintaining a desirable postural orientation the entire process that involves the relationship between sensory information and motor activity during postural control occurs without considerable cognitive effort. This relationship between sensory information and motor action has been systematically examined using the moving room paradigm in which visual information is manipulated through the movement of a room where the floor remains motionless, and corresponding body oscillation is observed (e.g., Barela, Barela, Rinaldi, & de Toledo, 2009; Barela et al., 2011; Jeka, Oie, & Kiemel, 2008). More interesting is the fact that under conditions of small-amplitude and low-velocity visual manipulation, participants couple to visual manipulation unconsciously (Barela et al., 2009; Freitas Junior & Barela, 2004), leading to the suggestion that such a relationship would be automatic (for a detailed discussion, see Stoffregen, Hove, Schmit, & Bardy, 2006).

Such an unconscious relationship between visual cues and body oscillation may be disrupted by verbal information and/or requirements. For example, Freitas Junior and Barela (2004) demonstrated that when participants were informed that the room was moving, the sensorimotor coupling strength was reduced, indicating that knowledge about visual manipulation leads to a reduction of corresponding body sway. Similarly, a request to resist the visual influence also leads to a reduction of the body sway response to the sensory manipulation (Barela et al., 2009). Based on these results, one can conclude that the relationship between visual information and motor action in postural control can be changed by prior information, leading to the suggestion that young adults alter sensorimotor coupling through intention. Such a possibility is quite intriguing and important because it might provide a means of altering functional dynamics to achieve behavioral goals of postural control.

Schöner, Dijkstra, and Jeka (1998) suggested that the postural control system can operate in two modes of functioning: self-motion and object-motion. In the self-motion mode, the postural control system detects changes in the visual flow field and interprets it as a self-motion, performing postural corrections as a result. The prevailing notion is that postural sway attempts to minimize a cost function such as ankle torque (Carver, Kiemel, van der Kooij, & Jeka, 2005) or retinal slip (Schöner, 1991). In most cases, the individual has no formal knowledge about the changes that take place. In the object-motion mode, the individual knows or learns that changes in the visual flow field are attributable to variations of the surrounding environment, and body sway corrections should not be necessary, in this case because of conscious involvement. In self-motion mode, verbal information (Freitas Junior & Barela, 2004) or a request to resist the optic flow (Stoffregen et al., 2006) leads to a change from the self-motion mode to the object-motion mode of functioning. In such a case, this change would imply that attention and cognitive

mechanisms are now involved in the task of controlling posture because the individual consciously has the goal of reducing the visual influence on body oscillation.

Altogether, these results suggest that the awareness of an environmental state, together with intention, can affect the relationship between sensory information and motor action. Although young adults have the ability to alter sensorimotor system functioning through intention (e.g., Barela et al., 2009), no study has examined whether the addition of cognitive loads that are unrelated to the functioning of the sensorimotor system affect this capability. A more refined relationship between sensory information and motor action is needed when task demands are increased (Prioli, Cardozo, de Freitas Junior, & Barela, 2006). Our hypothesis is that adding cognitive loads to the task of altering sensorimotor system functioning impairs performance in this task. Therefore, the purpose of the present study was to examine and compare the influence of conscious knowledge, intention, and cognitive load on the relationship between visual information, provided by the manipulation of a moving room, and body sway in postural control in young adults.

Methods

Participants

Sixteen healthy adults (21.88 ± 3.81 years of age) volunteered to participate in this study. The participants did not have any health problem that could affect their performance in maintaining an upright stance. They signed a written informed consent form that was approved by the Institutional Ethics Committee of Cruzeiro do Sul University.

Procedures

In a single visit to the laboratory, the participants were asked to stand inside a moving room. The room consisted of three walls (2.1 m length \times 2.1 m width \times 2.1 m height) and a ceiling mounted on wheels to allow its movement in the anterior/posterior (AP) direction while the floor remained motionless. The walls were covered with a pattern of white (42 cm wide) and black (22 cm wide) stripes. The movement of the room was produced by a servomotor mechanism, which consisted of a linear guide (Ottome, model PL6-90C-LD-MT-RC), stepper motor (Ottome, model SM3452808), and motor drive (Ottome, model MBD-8080DC) and was controlled by Motion Planner 4.3 software. Two fluorescent lights (20 W) were placed on the ceiling to maintain constant illumination. The moving room was moved at a peak velocity of 0.6 cm/s, with a peak-to-peak amplitude of 0.9 cm and frequency of 0.2 Hz. The parameters of room motion were chosen to maintain the frequency at 0.2 Hz, which corresponds to the natural frequency oscillation of the human body in an unperturbed quiet stance (Soames & Atha, 1982). Other studies have used the same parameters because they are known to strongly induce corresponding body sway (e.g., Aguiar & Barela, 2014).

The participants stood inside the room while fixating on a target that was placed on the front wall at a distance of 1 m. None of the participants had prior experience with or information about the room's movement and were requested to stand as still as possible with their feet placed comfortably apart at waist width. The participants performed a total of five trials, each lasting 60 s. In the first two trials, the room oscillated, and the participants were instructed to fixate on the target and stay as still as possible. No information was provided about the movement of the room, and none of the participants discerned that the room had oscillated (dynamic condition). Afterward, one trial was conducted in which the room oscillated and the participants were also instructed to fixate on the target in front of them. However, prior to this third trial, the participants were informed that the room would oscillate (information condition). Prior to the fourth trial, the participants were informed that the movement of the room induced corresponding body oscillation, but they should resist such an influence. Afterward, one trial was conducted according to this instruction (resisted condition). Finally, the participants performed one final trial in which they were requested to resist the visual influence of the room's movement and concomitantly count down from one hundred (100) to zero in steps of three (100, 97, 94, etc.; dual-task condition). To control backward-counting demands, the participants were instructed to reach zero within each trial.

To ensure that the participants were unaware of the movement of the room at the beginning of the experiment, a random sound (white noise) was provided during the entire experiment to mask possible auditory cues that emanated from the motor that moved the room. Additionally, the wheels on which the room was mounted were covered so that the participants were unable to see them.

One infrared emitting diode (IRED) was placed centrally on the participant's back at the scapula level (~8th thoracic vertebra), and another was placed on the front wall of the moving room to record information about body sway and room movement, respectively. One OPTOTRAK™ camera (Northern Digital, Waterloo, Canada) was positioned on the participant's back to track the IREDs at a sampling rate of 100 Hz. Kinematics data were filtered using a fourth-order zero-lag low-pass digital Butterworth filter with a cut-off frequency of 5 Hz.

Data processing

The average performance of the participants' postural control system was examined by calculating the variable mean sway amplitude and obtaining the standard deviation of the trunk sway signal in the AP direction within each trial after removing a first-order polynomial trend. The coupling between visual information and body sway in the AP direction was examined by employing the variables' coherence, velocity variability, gain, and phase.

Coherence was calculated through spectral analysis for each trial by computing the individual Fourier transforms of the trunk sway and moving room time series. Based on these transforms, magnitude squared coherence between body sway and the visual stimulus was computed at the stimulus driving frequency (0.2 Hz). Coherence measured how strongly body sway was coupled to the visual stimulus. Values close to 1 indicated that the signals had strong dependency between them, and values close to zero indicated weak or no dependency between the two signals.

The velocity variability of trunk sway was computed after the deterministic response to the sensory drive was subtracted (i.e., after postural responses at the driving frequency were removed; c.f., Jeka, Oie, & Kiemel, 2000). To perform this subtraction, the Fourier transform was computed, the value of the transform at the stimulus frequency was removed, and then the inverse transform was calculated, resulting in a "residual" velocity trajectory. Velocity variability was computed as the standard deviation of the residual velocity trajectory. This variable indicates body sway velocity at all frequencies, with the exception of the frequency of visual manipulation (0.2 Hz).

Gain and phase values were obtained through a transfer function (frequency response function), which was computed by dividing the Fourier transforms of trunk sway by the Fourier transforms of the visual stimulus, resulting in a complex-valued transfer function. Gain was the absolute value of the transfer function at the stimulus frequency, indicating the magnitude of the influence of visual information on body sway. A gain of 1 indicated that the response and stimulus amplitudes at the driving frequency were equal. A gain of < 1 or > 1 indicated that the response amplitude was higher or lower than the stimulus amplitude, respectively. Phase is the argument of the transfer function also at the stimulus frequency and is a measure of the temporal relationship between trunk sway and room movement. Positive/negative phase values indicate that body sway is behind/ahead of the moving room. Gain and phase values taken together indicate the coupling structure between body sway and visual information.

Statistical analysis

One analysis of variance (ANOVA) and two multivariate analyses of variance (MANOVAs) were used to test the effects of condition (dynamic, information, resisted, dual-task) on the dependent variables, with repeated measures. The dependent variable for the one-way ANOVA was mean sway amplitude. The dependent variables for each of the two one-way MANOVAs were coherence and velocity variability (first MANOVA) and gain and phase (second MANOVA). Appropriate follow-up univariate analyses and Tukey's Honestly Significant Difference *post hoc* tests were performed when applicable. The overall significance level was set at .05. All of the analyses were performed using SPSS 10.0 software.

Results

Figure 1 depicts the mean sway amplitude for all conditions. The ANOVA revealed no effect of condition on mean sway amplitude ($F_{3,45} = 1.82, p > .05, \eta^2 = .109$). Figure 2 depicts coherence and velocity variability values for all conditions. The MANOVA revealed an effect of condition (Wilks' Lambda = .475, $F_{6,88} = 6.62, p < .001, \eta^2 = .311$). The univariate analyses revealed an effect of condition on both coherence ($F_{3,45} = 6.64, p < .001, \eta^2 = .307$) and velocity variability ($F_{1,07,16.05} = 12.34, p < .003, \eta^2 = .451$). Coherence decreased in the information, resisted, and dual-task conditions compared with the dynamic condition. Coherence values were also lower in the resisted condition compared with the information condition. Finally, coherence decreased in the dual-task condition compared with the information and resisted

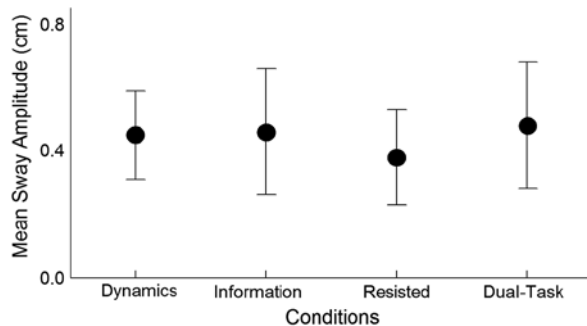


Figure 1. Mean sway amplitude values in the dynamic, information, resisted, and dual-task conditions. Error bars represent the standard deviation.

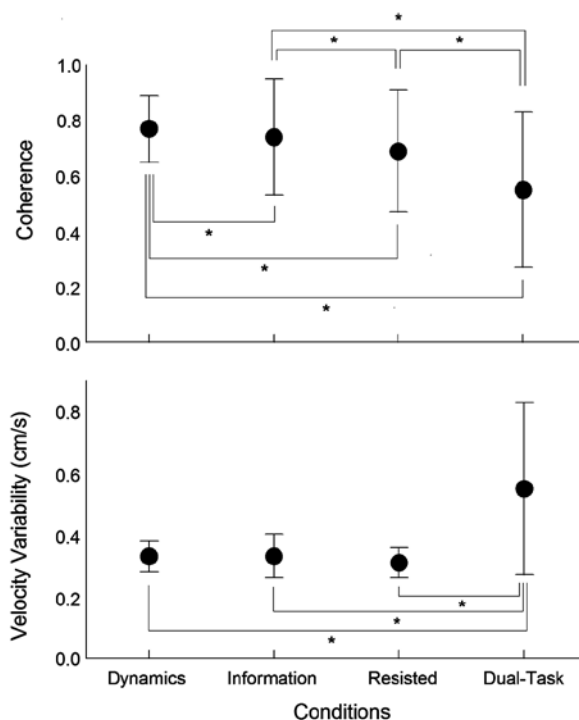


Figure 2. Mean coherence and velocity variability values in the dynamic, information, resisted, and dual-task conditions. Error bars represent the standard deviation.

conditions. Velocity variability was higher in the dual-task condition compared with the resisted, information, and dynamic conditions.

Figure 3 depicts the gain and phase values for all conditions. The MANOVA revealed an effect of condition (Wilks' Lambda = .664, $F_{6,88} = 3.33, p < .006, \eta^2 = .185$). The univariate analyses revealed an effect of condition on gain ($F_{3,45} = 6.23, p < .002, \eta^2 = .294$) but not phase ($F_{3,45} = 1.47, p > .05, \eta^2 = .090$). Gain values in the dynamic and dual-task conditions were not different from each other, and both were higher than in the resisted and information conditions. The resisted condition had lower gain values compared with the information condition.

The results of the counting task in the dual-task condition showed that the participants counted an average of 30.94 (± 9.23) numbers. To reach zero, a total of 35 numbers should be counted. An average of 6.81 (5.15) errors occurred, representing how many wrong subtractions were performed. Therefore, the participants were clearly able to successfully perform the counting task overall, nearly reaching zero during the trial.

Discussion

The purpose of the present study was to examine and compare the influence of conscious knowledge, intention, and cognitive load on the relationship between visual information and body sway in young adults while they maintained an upright stance. Our results clearly demonstrated that the coupling between visual information and body sway could be changed by intention because of information or a request to do so.

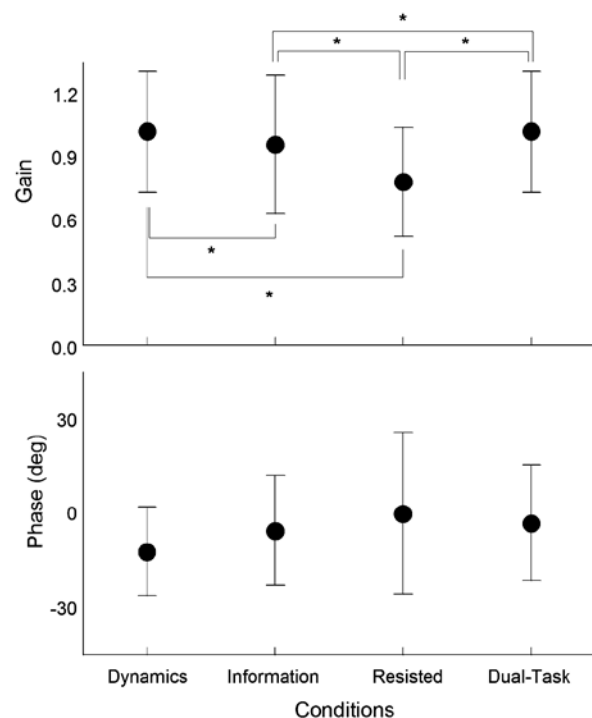


Figure 3. Mean gain and phase values in the dynamics, information, resisted, and dual-task conditions. Error bars represent the standard deviation.

However, changes in sensory motor coupling demand cognitive effort such that while performing a dual-task, individuals are influenced by visual information but with less coherent and more variable motor responses.

The manipulation of visual information without prior information induced corresponding body sway, as previously reported (Barela et al., 2009; Dijkstra, Schöner, & Gielen, 1994; Freitas Junior & Barela, 2004; Jeka et al., 2000; Stoffregen et al., 2006). In all of these previous studies, the manipulation of the visual surroundings continuously led to corresponding inductions of body sway, without the participants' awareness that body sway occurred. Such an effect was even suggested to be automatic (for a detailed discussion, see Stoffregen et al., 2006) but depended on stimulus characteristics (Barela et al., 2009). As Schöner (1991) suggested, body sway is induced in a self-motion fashion in which sway is performed because the retinal slip caused by manipulation of the visual surroundings is interpreted by the central nervous system as the individual's sway.

We suggest that such coupling between visual information and body sway without any intentional awareness indicates that the central nervous system has intrinsic dynamics that do not regularly require the participation of any higher cognitive center to interpret visual changes and perform corresponding body responses. Such a mechanism is quite clever because it allows the central nervous system to use attentional and cognitive resources to perform tasks other than the ones related to postural control. Moreover, the suggested intrinsic dynamics are also able to accommodate abrupt changes in visual cues and reduce the induced postural response (Barela et al., 2009; Jeka et al., 2008). Again, such a reduction of utilizing visual cues does not imply that the participants were aware of such changes (Barela et al., 2009) and is characterized by complex mechanisms that consist of slow and rapid adaptive processes that reflect asymmetrical postural responses (Jeka et al., 2008) and involve inter-modality sensory cues (Polastri, Barela, Kiemel, & Jeka, 2012).

Despite constituting an important functional feature to accommodate a rich and continuously changing stimulus-rich environment and maintaining flexible and adaptive postural control function, in many cases such intrinsic dynamics can be changed by prior knowledge, which was demonstrated long ago (Horak, Diener, & Nashner, 1989). More recently, verbal information about visual manipulation also reduced induced body sway (Barela et al., 2009; Freitas Junior & Barela, 2004; Stoffregen et al., 2006). Our results corroborate these previous findings in which we observed a reduction of gain values in the information and resisted conditions compared with the dynamic condition. Moreover, coherence values were also lower for the same comparison. Therefore, prior knowledge about visual manipulation reduced the coupling between visual information and body sway, indicating changes in the intrinsic dynamics of postural control functioning.

The present results advance our knowledge, indicating that requiring a specific action affects visual information and body sway coupling even more than just providing information that visual manipulation will take place. Both the gain and coherence values were lower in the resisted condition than in the information condition. One possible explanation is that changes in intrinsic dynamics involve cognitive effort. In the case of a more specific situation (i.e., only knowing that the room would move against knowing that the room would move and that one should resist its influence), one could better specify the cognitive strategy. Specifically, in the resisted condition, the participants were told what should be done, whereas in the information condition, the participants individually needed to decide what should be done. Therefore, to change specific intrinsic dynamics, more directed and well-defined instructions work better than general and open information.

Another interesting aspect of the present results, which corroborate previous studies (e.g., Barela et al., 2009; Barela, Weigelt, Polastri, Godoi, Aguiar, & Jeka, 2014), is that independent of condition, visual manipulation could not be totally avoided. Despite knowing and being requested to resist the movement of the surrounding environment, the participants were still influenced by visual manipulation, indicating that the central nervous system cannot ignore available sensory information, even if it provides inaccurate information. Such a postural control functioning characteristic can also be exemplified in cases in which inaccurate visual input through sway-referencing is far more disruptive to postural control than the lack of visual cues (Nashner & Berthoz, 1978; Vidal, Berthoz, & Millanvoye, 1982). An additional assertion is that it can also be observed when an individual has knowledge about the inaccuracy of visual cues. Ignoring and avoiding imprecise visual information are the final consequences of intricate sensory integration in which different weights are assigned to the available sensory cues (Jeka et al., 2000, 2008), which is a process that involves cognitive components.

Any change in intrinsic dynamics caused by knowledge or a request to do so is mediated by a cognitive costly process. Despite knowing and being requested to resist the visual manipulation, as long as a simultaneous task is performed, the participant's body sway is induced similarly to the intrinsic condition, reflected by the gain values. The backward counting task requires cognitive effort. In performing the task, fewer resources, if any, remain to change the intrinsic dynamics that involve visual information and body sway. Consequently, in the dual-task condition, the visual manipulation induced more corresponding body sway compared with the information and resisted conditions.

Moreover, our results showed that despite being influenced by the visual manipulation when counting backward (i.e., with similar gain values in the dynamic and dual-task conditions), body sway coincided less with the visual cues and had higher velocity variability.

These results indicate that when cognitive resources were directed to performing the backward counting task, body sway was induced, but its quality was affected. Two reasons may explain the body sway differences in the dual-task condition. First, even in the intrinsic dynamics condition in which well-established coupling between visual information and body sway is already in place, some cognitive involvement is still required, even if it is not noticeable by the participant. Second, knowing that the room was moving and one should resist it, the individual tried to avoid such an influence. However, because of the concomitant task, insufficient cognitive resources were available to meet such a requirement. Therefore, body sway was slightly disrupted. Finally, a combination of both of these possibilities may have been involved, such that some cognitive functions are still needed even in the dynamic condition and also in the dual-task condition, the individual attempted to follow the instructions and not oscillate with the room, but because of limited cognitive resources, the participant could not accomplish the task but only disrupted body sway quality. Unfortunately, because of the present experimental design, we cannot rule out any of these possibilities.

Importantly, the temporal relationship between the visual stimulus and body sway was the only characteristic of sensorimotor coupling that was unaltered by the manipulations in the present study, reflected by the lack of an effect of condition on phase. Body sway remained in phase with room motion during all of the trials. This result was expected because both a request to resist the visual influence and adaptation following abrupt increases in room velocity were able to alter the magnitude of the influence of room motion on body sway but not the temporal relationship between the two signals (Barela et al., 2014).

All cognitive manipulations that were used in the present study affected the strength and quality of the coupling of body sway to visual cues but not the overall sway magnitude, reflected by the lack of an effect of condition on mean sway amplitude. Overall body sway is a measure that is commonly used in studies that investigate cognitive involvement in postural control (e.g., Baratto, Morasso, Re, & Spada, 2002; Kiers, van Dieen, Dekkers, Wittink, & Vanhees, 2013). However, our results demonstrate that such a measure does not reveal important aspects of postural control. The lack of an effect of condition on mean sway amplitude might be attributable to its lower sensitivity to the detection of changes in postural performance caused by cognitive loads compared with the other variables that closely examined the relationship between visual cues and postural responses instead of simply overall body sway. The results of the present study advance our knowledge of the cognitive contributions to overall body sway in postural control and the gathering of sensory information as a basis for the production of motor activity that one needs to perform for postural control.

In conclusion, the present results demonstrated that intention plays an important role in sensorimotor

system function, changing action-perception patterns in the postural control system whenever required and corroborating previous studies (Barela et al., 2009; Freitas Junior & Barela, 2004). The present study provided evidence that such changes demand cognitive effort because these changes were not observed when intention was simultaneously present with a cognitively demanding task. For this reason, behavior changes in the postural control system with regard to gathering sensory information for the production of motor activity are consciously available. However, attention needs to be employed for this entire process, thus limiting cognitive resources for other environmental goals. Future studies should extend our findings by investigating whether the presence of cognitive loads, such as with the counting task used in the present study, affects sensorimotor coupling when individuals have no intention to change action-perception patterns. Such studies may determine whether cognition affects the intrinsic dynamics of the postural control system and the extent to which sensorimotor coupling occurs automatically (e.g., Barela et al., 2011).

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