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Contributions of delayed visual feedback and cognitive task load to postural dynamics

Ting Ting Yeh[a], Jason Boulet[a,b], Tyler Cluff[a,b], Ramesh Balasubramaniam[a,b,*]

[a] Sensorimotor Neuroscience Laboratory, Department of Kinesiology, McMaster University, Hamilton, ON, Canada L8S 4K1
[b] Sensorimotor Neuroscience Laboratory, McMaster Institute for Neuroscience Discovery and Study (MiNDS), McMaster University, Hamilton, ON, Canada L8S 4K1

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ABSTRACT

In this experiment, we examined the extent to which postural control is influenced by visual and cognitive task performance. Fourteen healthy young participants performed a balance task in eyes-open (EO) and delayed visual feedback (DVF) conditions. DVF was presented at delays ranging from 0 to 1200 ms in 300 ms increments. Cognitive load was implemented by a simple, serial arithmetic task. High and low-pass filtering (f_c = 0.3 Hz) distinguished LOW and HIGH frequency components, which were used to compute the variability of Anteroposterior (AP) Center of Pressure (COP) trajectories on fast (>0.3 Hz) and slow (<0.3 Hz) times cales. Imposed visual delay increased sway variability at both LOW and HIGH components. Cognitive task performance, however, influenced only the variability of fast (HIGH) sway components. Our results support distinct timescale mechanisms for postural control, but also demonstrate that vision predominantly influences low frequency components of postural sway. Moment-to-moment COP fluctuations are dependent on cognitive performance during delayed visual feedback postural control.

Standing balance requires that the vertical projection of the body's centre of mass remain within the bounds of the physical support. Postural control is a complex process involving mechanisms that support the maintenance of upright stance in response to self and environmental perturbation [2]. Mechanisms that contribute to postural control are served by distinct neurophysiological pathways and dynamical control structures that incorporate both closed and open-loop processes [1,2,6]. The control of posture is a complex physical task in and of itself, with multiple physical degrees of freedom in the joint-muscle space that must be assembled appropriately to stabilize the postural system.

Postural control works through the assembly of synergies featuring the interplay of visco-elastic and reflexive muscle dynamics with adaptive mechanisms that reflect both anticipatory and compensatory components. The integrity of these control mechanisms is dependent on the salience of multimodal sensory feedback, which stems from visual [2,19], vestibular [10], and somatosensory (proprioceptive) [11,15] sources. Of the sensory modalities that contribute to posture, vision appears to be the dominant information source for the control of standing balance [2,24]. A large number of studies distinguish between mechanisms that support eyes-open and eyes-closed postural control, or selectively manipulate the integrity of visual feedback by sensory perturbations, using moving room displays, for example [20]. Several of these studies have also examined the dependence of posture on the spatial salience of or lack of visual feedback. More recently researchers have investigated the extent to which postural control is influenced by the temporal integrity of visual feedback [3,34].

Delayed visual feedback (DVF) is a technique that can be implemented to determine whether postural control is influenced by the temporal contiguity of visual feedback [3,28,29,34]. Though small temporal delays for visual feedback reduce sway variability [28], subsequent research has demonstrated that DVF has a generally destabilizing influence on posture. Said differently, the magnitude of sway variability appears to be proportionate to visual delay [3,34].

The complexity of control is further exacerbated by the fact that individuals often engage in secondary task performance while standing—rarely is posture controlled solely to maintain standing balance. Therefore it is important for research to take into consideration the interaction between secondary task performance (physical or cognitive) and the neurophysiological and dynamical mechanisms for postural control. To address the cognitive penetrability of standing balance, postural and cognitive tasks are typically combined in the dual-task experimental paradigm [18]. These studies have revealed that there is a great deal of interaction between high-level cognitive processes and postural control, a result that might seem surprising if postural control is viewed as spinal or

* Corresponding author at: Sensorimotor Neuroscience Laboratory, McMaster University, 1280 Main Street West, Hamilton, ON, Canada L8S 4K1.
Tel.: +1 905 525 9140x21208; fax: +1 905 523 6011.
E-mail address: ramesh@mcmaster.ca (R. Balasubramaniam).

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sub-cortical in nature and cognition is considered purely cortical. However, a large body of research over the last two decades has shown that neither of these two views is tenable nor accurate. The cerebellum has been implicated in sensory processing and cognition and there is growing evidence of cortical involvement in postural reflexes [2].

Though several studies have considered reciprocal postural-cognitive influences in dual-task performance, consensus regarding the interaction between posture and cognition has yet to be established. While some studies report an increase in postural sway when performing a cognitive task, others report the converse [2,13,27]. The inconsistency of results might reflect methodological differences in postural assessment, task load and the timescales studied in the analysis method. Dual-task studies typically manipulate the difficulty of the postural component by varying stance [7,12,16,18], somatosensory [4,23,27] or visual input [2,9,12,14], or any combination of these factors [12,30,32], which might also precipitate the inconsistency of the findings.

The dynamical structure of postural fluctuations has attracted considerable interest in recent years. A variety of analysis techniques [2,3,34,38] have revealed that postural sway has two characteristic timescales. A fast (or high frequency) timescale capturing rapid processes that reflect open-loop control or exploratory activity is complemented by a slower (low frequency) timescale that reflects corrective or feedback based control processes [2,3,34]. The effect of DVF on the two timescales of postural fluctuations, especially during the performance of secondary cognitive tasks has only been studied to a limited extent [34].

In this experiment we sought to examine the relative contributions of visual feedback delay and cognitive task load on postural dynamics. Specifically, we manipulated the temporal salience of visual feedback by imposed feedback delay. We graded the integrity of the visual feedback in a visual tracking task by varying the delay of the stimulus from 0 to 1200 ms in 300 ms increments [3,28,34]. The purpose of this experiment was to determine the manner in which DVF interacted with cognitive load to influence postural control. Secondly, we ask if DVF and the secondary cognitive task differentially influence the two timescales (slow and fast) commonly observed in postural control. Cognitive load, in this context, was implemented by a simple, serial arithmetic task [36]. On the basis of those manipulations, we sought to distinguish timescale-dependent postural control mechanisms and the influence of visual and cognitive task components for standing balance. Our purpose is consistent with the view that postural sway can be divided into two characteristic timescales. Therefore, the questions we address in this experiment are (1) whether cognitive load and delayed visual feedback interact to influence postural control and (2) if distinct timescale mechanisms for postural control are influenced by visual and cognitive task performance.

Fourteen healthy young participants (6 males and 8 females; age = 24.64 ± 4.27 years; mass = 63.34 ± 9.60 kg; height = 166.94 ± 7.88 cm) participated in this study. Participants reported no visual, orthopedic or neurological disorders. Participants provided written informed consent. The experimental protocol was approved by the Ethics Review Board at McMaster University prior to the experiment. COP time series were collected by a force platform (OR6-2000, AMTI, Newton, MA, USA) sampled at 1000 Hz. Delayed visual feedback of the COP position was implemented by custom MATLAB™ code (7.9.0, The Mathworks, Natick, MA, USA).

Participants were asked to stand on the force platform with arms placed at their sides and maintain a comfortable posture. A 19 inch LCD monitor located at eye level, 70 cm in front of the platform provided visual feedback of the COP location. A red dot (13 mm) at the center of the monitor corresponded to the visual target. A smaller white dot (10 mm) represented (real-time or delayed) COP position. Participants were instructed to position their COP (white dot) as close to the fixed target (red dot) as possible for visual trials. The gain factor-relating COP to the visual feedback of the COP was set at 5. Previous work [28,29] did not report differences in performance for gain factors ranging from 2 to 20. The display apparatus had a lag time that ranged from 43 to 81.5 ms due to machine processing delays and the operating system. Foot position for individual participants was determined prior to the experiment and corresponded to the position where the least amount of effort was spent to make COP position overlap onto the visual target. Foot positioning was kept constant for all trials.

In the dual-task conditions, participants performed a simple, serial arithmetic task. Prior to trial onset, participants received a two-digit number between 48 and 68. Participants performed a series of six randomized arithmetic operations (addition or subtraction) at a rate of one computation per 5 s interval. They computed the running sum of operations and verbalized their response following trial completion, thereby eliminating articulation effects for COP displacements [8]. The experiment consisted of 12 conditions: eyes-open (EO) and 5 delayed visual feedback (DVF) conditions: 0, 300, 600, 900 and 1200 ms, with and without a concurrent mental arithmetic task (Control, COG). In the EO condition, only a stationary visual target (red dot) was shown, without COP position feedback. The 0 ms condition refers to the participant receiving real-time feedback about their COP location. Five 31 s trials were performed in each condition, resulting in a total of 60 trials per participant. Trial order was randomized within blocks (all conditions were randomly presented within each block) to minimize learning effects.

The first 1.2 s of collected data accounted for the length of the maximum visual delay. Therefore, only the last 29.8 s of each trial were used for AP COP time series analysis. Time series were coarse-grained by a non-overlapping, 10 sample moving average, resulting in a time series of 2980 points and an effective sampling frequency of 100 Hz. Next, the time series were mean-detrended. Subsequently, COP time series were filtered according to [34] which translated to time series consisting of low (LOW) and high-pass frequency (HIGH) components (Fig. 1). Filtering was performed using a dual-pass, second-order Butterworth filter with a cutoff frequency of 0.3 Hz. Subsequent linear trends were removed from the LOW and HIGH time series using well established techniques used by van den Heuvel et al. [34]. The untreated time series are referred to as UNFILTERED for the remainder of the manuscript. Standard deviations were computed from each time series (UNFILTERED, LOW and HIGH).

Mean differences in sway variability (standard deviation) were contrasted across DVF and dual-task cognitive conditions using a 2 (Control, COG) × 6 (DVF: EO, 0, 300, 600, 900, 1200 ms) analysis of variance (ANOVA) with repeated measures. The Greenhouse–Geisser correction factor for statistical degrees of freedom was used to correct sphericity violations (Mauchly's Test, $p < 0.05$). Post hoc analysis was performed with Bonferroni corrections for pair-wise means comparisons.

The main findings of the study are illustrated in Fig. 2. As shown in the left panel for UNFILTERED data, sway variability was dependent on imposed visual delay ($F(2.43, 31.62) = 10.29$, $p < 0.01$) and cognitive task performance ($F(1, 13) = 5.74$, $p < 0.01$). There was no significant DVF × COG interaction ($F(2.74, 35.67) = 0.23$, $p > 0.05$). Pair-wise comparisons revealed that sway variability in the 0 ms condition ($M = 1.93$, SE = 0.11 mm) was reduced relative to the 600 ms ($M = 2.29$, SE = 0.10 mm) ($p < 0.001$), 900 ms ($M = 2.59$, SE = 0.15 mm) ($p < 0.01$), and 1200 ms conditions ($M = 2.55$, SE = 1.6 mm) ($p < 0.001$). Moreover, the 300 ms condition ($M = 2.01$, SE = 0.11 mm) was reduced relative to the 600 ms ($p < 0.01$), 900 ms ($p < 0.01$) and 1200 ms conditions ($p < 0.001$). The addition of the cognitive dual-task reduced sway variabil-