



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) timescales. 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.

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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).

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 posi-

tion. 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) \times 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 \times 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-

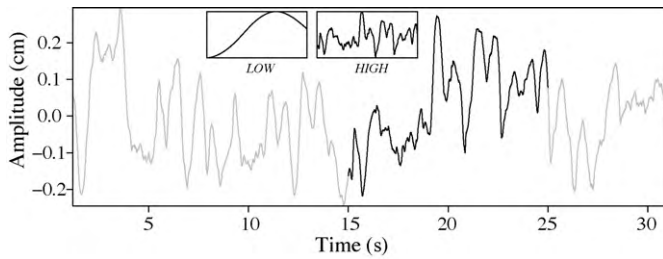


Fig. 1. A sample time series plot of the Anteroposterior COP of a participant performing the 300 ms DVF condition with a cognitive task shown from 1.2 to 31 s. For the purpose of demonstration, LOW and HIGH frequency components of the COP are shown for the highlighted time interval (15–25 s). Filtering was performed using a dual-pass, second-order Butterworth filter with a cutoff frequency of 0.3 Hz. Subsequent analysis was performed for entire original (UNFILTERED), low and high-pass filtered time series.

ity relative to the control delayed visual feedback condition ($p < 0.01$).

For the LOW data, sway variability was dependent on the temporal salience of visual feedback ($F(2.59, 33.62) = 4.58$, $p < 0.05$), but was not influenced by cognitive load ($F(1, 13) = 1.69$, $p > 0.05$). We also did not see a significant interaction between DVF and the cognitive task. Sway variability was reduced when COP position feedback was real-time or 0 ms ($M = 0.92$, $SE = 0.06$ mm) relative to 600 ms ($M = 1.21 \pm 0.07$ mm) ($p < 0.001$), 900 ms ($M = 1.20$, $SE = 0.09$ mm) ($p < 0.05$), and the 1200 ms delay conditions ($M = 1.21 \pm 0.10$ mm) ($p < 0.05$). Sway variability was reduced for the 300 ms ($M = 1.05$, $SE = 0.07$ mm) relative to 600 ms delay condition ($p < 0.01$). These results are summarized in the middle panel of Fig. 2.

Sway variability of the high-pass filtered COP trajectories (HIGH) was dependent on visual feedback ($F(1.62, 21.05) = 10.75$, $p < 0.01$) and cognitive task component ($F(1, 13) = 9.97$, $p < 0.01$), but the DVF \times COG interaction, ($F(1.83, 23.84) = 1.41$, $p > 0.05$) was not significant. A careful inspection of Fig. 2 (right panel) reveals that cognitive load reduced the variability of high-pass filtered AP COP time series. Although sway variability monotonically increased with longer time delays, post hoc analyses revealed a statistical difference only for the following. Sway variability was reduced in the EO ($M = 1.23$, $SE = 0.07$ mm) relative to 0 ms ($M = 1.51$, $SE = 0.08$ mm) ($p < 0.05$), 300 ms ($M = 1.48$,

$SE = 0.07$ mm) ($p < 0.01$), 600 ms ($M = 1.61$, $SE = 0.07$ mm) ($p < 0.001$), 900 ms ($M = 1.88 \pm 0.13$ mm) ($p < 0.05$), and 1200 ms ($M = 1.82$, $SE = 0.12$ mm) ($p < 0.05$) conditions. Also, sway variability was reduced in the 300 ms relative to 600 ms condition ($p < 0.05$).

This study examined the extent to which sway variability was influenced by the interplay between delayed visual feedback and cognitive task performance in an upright postural task. We examined whether the magnitude of sway variability attributable to imposed visual delay and cognitive load combined interactively or independently influenced postural control. We implemented a two-timescale model for postural control, decomposing sway variability into distinct frequency components by low (LOW) and high-pass filtered (HIGH) COP time series. Our results show that sway variability computed from UNFILTERED and low-pass filtered COP time series increased as a function of the visual delay. In contrast, concurrent cognitive performance reduced the variability of both UNFILTERED and high-pass filtered AP COP time series. Imposed visual feedback delay and cognitive load make distinct contributions to postural stability. This appears to be based on the frequency composition of the enacted control mechanism.

Previous studies that examined the influence of conjoint cognitive performance on sway variability have generated inconsistent and often-times paradoxical results. Perturbed [25], reduced [2] and unaffected [7] sway variability have been reported for dual-task posture-cognition studies. In addition to these inconsistent findings and lack of consensus on the role of cognition in posture control, a clear determination of mechanisms by which cognition influences sway variability does not appear to exist [2,29]. In the present study, we applied a systematic analysis that parsed sway variability into LOW and HIGH frequency components. Our results demonstrate that reduced sway variability in the dual-task cognitive condition is attributable to reduced amplitude in the fast component that defines moment-to-moment COP fluctuations.

Imposed visual feedback delay resulted in increased sway variability in UNFILTERED and low-pass filtered COP time series, which demonstrates that vision operates on a characteristically slow timescale. However, when a task with low to moderate cognitive load was added, we found the control mechanisms switch to a more efficient, automatic process, thereby stabilizing and reducing postural fluctuations. Consequently, we concluded that serial

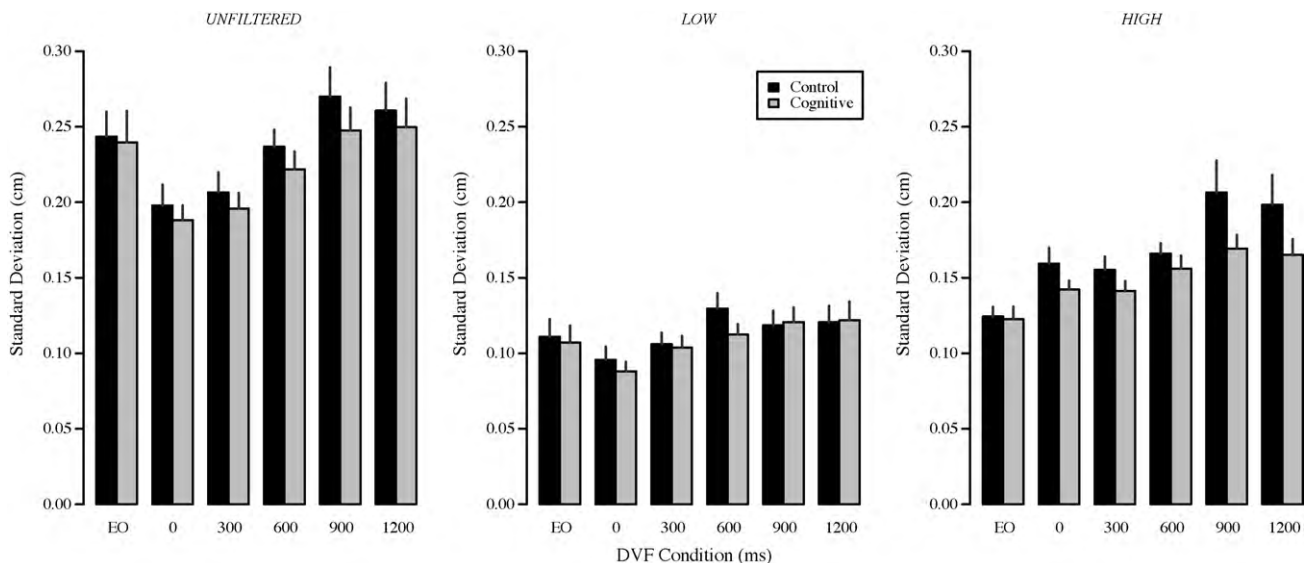


Fig. 2. Standard deviations of the UNFILTERED, LOW and HIGH AP COP time series for EO and DVF conditions (0, 300, 600, 900, 1200 ms) in the presence and absence of the cognitive dual task. The control condition is shown in black while the cognitive dual-task condition is shown in grey. Error bars represent ± 1 standard error.

arithmetic tasks under the presence of DVF affected the faster time-scale component of postural sway. One might argue that these results are consistent with the autonomous viewpoint for postural control [16]. According to this viewpoint, imposed cognitive demand diverts attentional resources to secondary task performance [16,23,35]. One could also argue that these results also support the facilitatory viewpoint of postural control which suggests that the purpose of the postural system is to facilitate or enable suprapostural task performance, cognitive or physical [2]. Proponents of the facilitatory viewpoint [27] have argued that in a stable postural context, the role of the postural system is to minimize sway to the extent that it facilitates concurrent task performance – physical or cognitive. When performing cognitive tasks one could make the case that posture control is more likely relegated to low-level subsystems that are governed by reflexive and compensatory mechanisms [33].

Sway in the AP axis is largely governed by rotations about the ankle joint involving plantarflexion and dorsiflexion. Several studies have proposed the underlying low-level mechanism for reduced sway variability in dual-task cognitive performance is related to ankle joint stiffness [2,7], which is reflected by increased frequency, reduced amplitude COP excursions. This proposition is consistent with our data and may reflect increased tonic drive to musculature spanning the ankle joint. Another plausible mechanism involves damping about the ankle joint, which is mediated by increased stretch reflex gain. Postural control characterized by increased autonomy of control proffers from increased stringency reflex activation, a process that is governed by lower level control systems. The involvement of these lower level control mechanisms need to be tested in future studies using electrophysiological and biomechanical analyses of the ankle joint.

In the present study, we limited our analyses to the AP axis. In future work, it would be interesting to apply this method to radial sway and fluctuations specific to the mediolateral (ML) axis [21]. The influence of cognitive tasks on ML fluctuations and the underlying lower-limb dynamics (hip loading/unloading and ankle stiffness/damping) need to be explored in a future study using spectral techniques. Important questions regarding the independence of the control processes governing AP and ML sway could also be tested using this paradigm.

There are some important caveats to note about the filtering method that we used to separate the fast and slow timescales in postural control. Following previous work from our laboratory by van den Heuvel et al. [34], we chose a frequency-based method to identify control mechanisms that underlie stance regulation. It would be interesting to see the present results corroborated by employing other methods used to infer dual time-scale postural mechanisms such as the rambling/trembling decomposition [38], statistical mechanics based approaches and autocorrelation functions [2,3,6] and dynamical systems analysis using higher dimensional embedding [2,9]. Furthermore, the term “distinct” timescales should be exercised with caution when referring to the outcome of frequency-based analyses. The frequency spectrum in postural sway does not typically show distinct peaks that correspond to low and high frequency contributions. For example, in a recent wavelet-based analysis, Chagdes and co-workers [5] illustrated the scale-invariant properties of postural sway [5]. Following this work, it appears that nearly all timescales seem to contribute actively to standing balance.

Upright balance control in the wake of DVF and attentional dual tasks is of particular interest in the study of aging. It has been suggested that there is an increased likelihood of destabilization during the performance of cognitive dual tasks in the elderly [17,22,26,31]. This has been attributed to reduce lower limb muscle strength, diminished information processing capacity, and most

importantly, the age-related decline in multisensory integration [37]. The present study is of particular relevance in older adults, who also suffer from greater delays in the processing of sensory information. We are currently pursuing the issue of how DVF and cognitive load influence postural control in older adults.

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