Exp Brain Res (2010) 203:647–658
DOI 10.1007/s00221-010-2274-7

RESEARCH ARTICLE

Attentional influences on the performance of secondary physical tasks during posture control

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Received: 14 January 2010 / Accepted: 17 April 2010 / Published online: 8 May 2010

Abstract We examined the influence of attentional focus and cognitive load on motor performance in a dynamic stick balancing task during the maintenance of upright posture. Dynamical analyses of postural fluctuations revealed the existence of a drift and correct mechanism, with correlational structure reflecting the demands of the stick balancing task. In contrast, experimentally manipulated attentional foci (internal, external) did not influence the variability of postural or fingertip trajectories. However, dual-task cognitive stick balancing performance resulted in decreased variability of postural and fingertip time series. These results are discussed in the context of dual timescale models for posture control and stick balancing.

Keywords Posture control · Suprapostural tasks · Focus of attention · Stick balancing · Dynamical systems · Variability in motor control · Motor learning and expertise

Introduction

The control of upright posture and balance is a complex physical task, with multiple physical degrees of freedom in the joint-muscle space that must be assembled appropriately to stabilize standing balance (Ting 2007). However, while maintaining balance, we frequently perform concurrent secondary tasks, both physical and cognitive. Superordinate to the control of posture, the tasks are typically referred to as suprapostural tasks (Stoffregen et al. 1999; Mitra 2003). Suprapostural influence on balance control has received considerable attention (see Balasubramaniam and Wing 2002 for review). Of particular interest has been the role of attentional focus on the performance of conjoint physical and cognitive tasks during stance.

In recent years, several studies contributed to a generalized theory of attentional influences on motor performance (see Wulf and Prinz 2001 for review). Emanating from this research, the “constrained action” theory proposes that attention devoted to movement execution interrupts the automaticity of performance (Wulf et al. 2001; Wulf and Prinz 2001; McNevin and Wulf 2002). Performance, defined as the statistical stability or variability of motor execution, is dependent on whether attention is devoted to motor execution or outcome.

Within this body of research, a consistent finding is that external focus, defined as attention devoted to motor outcome, stabilizes performance. In contrast, internal focus, where attention is directed to motor execution, inhibits learning and performance (Shea and Wulf 1999; McNevin et al. 2003). The stabilizing external focus is thought to minimize interference between conscious intervention and the automaticity of motor performance, thereby allowing the motor system to self-organize more effectively (Wulf et al. 2001). Motor automaticity (Milton et al. 2004) is supported by reduced probe reaction time, which suggests resource competition is reduced when the focus of attention is external (Wulf et al. 2001). Internal focus is thought to compromise performance by constraining biomechanical degrees of freedom that contribute to motor execution (McNevin et al. 2003; McNevin and Wulf 2002).

The attention–performance relationship can be investigated by experimental paradigms that impose cognitive

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(Lajoie et al. 1993; Dault et al. 2001; Doumas et al. 2009) or physical (Riley et al. 1999a, b) task load. These studies demonstrated that postural and suprapostural task performance, quantified in terms of posture and movement variability, is dependent on whether the focus of attention is internalized or externalized (Wulf et al. 2003). Furthermore, the prioritization of postural or suprapostural performance is dependent on the congruency of task goals (Balasubramaniam and Turvey 2000; Balasubramaniam et al. 2000). A very good paradigm for studying the role of physical performance and attentional focus on postural control is the stick balancing task.

Human stick balancing kinematics show complex, multi-scale dynamical properties (Milton et al. 2009a; Cluff and Balasubramaniam 2009). Stick fluctuations with respect to the vertical conform to a generalized scaling law characteristic of on–off intermittency (Cabrera and Milton 2004). Dynamical intermittency reflects a discontinuous control characterized by periodic switching between approximately constant dynamical state and large-scale corrective movements. With experience, fingertip trajectories become less correlated but are convergent (within recurrence radius ε), demonstrating that fluctuations reflect and contribute to the performance stability (indexed by mean balancing time) acquired as a function of stick balancing expertise (Cluff et al. 2009).

In this study, we examined the influence of focus of attention on the statistical stability (movement variability) of fingertip (FINGER) and center of pressure (COP) trajectories in experienced stick balancers. Subjects balanced a wooden dowel on the index finger. Internal focus was implemented by instructing participants to minimize fingertip displacement when stick balancing. In contrast, an external, task-relevant focus was implemented by instruction to minimize stick deviation from the upright position. External, task-irrelevant focus was implemented through concurrent cognitive load in the form of a serial arithmetic task.

The attention–performance relationship was delineated through a series of experimental conditions that differed in terms of instructed foci. These tasks constituted dual-task suprapostural and postural performance (P-SBEXT: posture-stick balancing, externalized focus; P-SBINT: posture-stick balancing, internalized focus). In contrast, we implemented a triplicate condition through conjoint postural, stick balancing and cognitive components (P-SB-CDT). The imposed cognitive load was motivated by evidence that cognitive load increases stick balancing survival times (Milton et al. 2008a). Furthermore, we took into consideration that the acquisition of stick balancing expertise is characterized by stochastic fingertip deviations—control is discontinuous and characterized by ballistic corrections (Milton et al. 2008a; Cluff et al. 2009). Fingertip deviations, therefore, show dynamical properties on distinct timescales. For short timescales, fingertip deviations appear to fluctuate about a drifting equilibrium. Conversely, over long timescales, fingertip deviations are corrective. However, we know little about whether cognitive load influences the stochastic (fluctuations) or deterministic component of serial fingertip and center of pressure increments.

The purpose of this study was to determine the influence of focus of attention and cognitive load on postural and suprapostural performance in experienced stick balancers. In addition, we questioned whether suprapostural activity could mediate the interplay between deterministic and stochastic postural and fingertip components of stick balancing—corrective versus fluctuating displacements (Collins and De Luca 1994, 1995).

The congruency of statistical stability (i.e., reduced variability) and dynamical stability of trajectories has been the subject of debate in motor control (*cf*. Riley and Turvey 2002). While some authors access stability through a non-linear embedding that indexes spatiotemporal variability and dynamical structure in series (Riley et al. 1999a, b), others argue for the spectral decomposition of position increments. Scaling laws from the double-logarithmic power spectrum–frequency relationship are used to infer dynamical stability (Delignières et al. 2006). Still others support the information theory perspective and consider variable increments favorable due to the inherent generation of proprioceptive information (Riley et al. 1997a, b). Finally, variability is often considered favorable because it facilitates flexible sensorimotor dynamics (Freitas et al. 2005; Latash and Anson 2006).

In this experiment, we sought to identify attentionally mediated changes in the global spatial variability of stick balancing FINGER and COP trajectories. We modeled COP and FINGER dynamics as two-dimensional random walks to determine underlying mechanisms for reduced spatial variability. We chose statistical mechanics methods for this analysis (Mandelbrot and van Ness 1968; Collins and De Luca 1995). In such a way, we combine a line of work focused on the statistical stability of performance and a timescale-dependent dynamical analysis. This analysis determines distinct variability components by quantifying the magnitude of correlation in series—persistent versus anti-persistent displacements—and the characteristic timescales on which they operate. Finally, these analyses were supplemented by spectral decomposition of COP and FINGER time series.

We predicted reduced variability fingertip and COP trajectories in the triple-task posture, cognitive and stick balancing condition—trajectories would be less persistent on short timescales. This hypothesis was derived from research that examined performance stability when focusing on external, task-irrelevant cues (Weeks et al. 2003).

Finally, we hypothesized that temporal coupling between COP and fingertip position would change as a function of attentional focus for balancing. Specifically, we predicted that the external focus would result in a temporal relationship whereby fingertip deviations were prioritized. We also hypothesized that COP would temporally lag fingertip movements and produce compensatory movements over longer timescales.

To our knowledge, this is the first study to perform a mechanistic, dynamical analysis of attentional influences on motor performance. We determined whether the external, task-relevant focus of attention contributes to performance stability in individuals familiar with a complex balancing task, and secondly, distinct timescales over which attentional influences might operate to facilitate (external focus) or detract (internal focus) from performance.

Materials and methods

Ten healthy subjects (7 men; 3 women; aged 19–27) from the McMaster University student community participated. Participants were sport science graduate and undergraduate students recruited from a learning study that examined the acquisition of stick balancing expertise (Cluff et al. *in preparation*). Participants had normal or corrected vision, with no history of neurological or musculoskeletal disorder. The protocol was approved by the Institutional Review Board with participants providing written informed consent prior to the experiment.

Transverse plane (ML; AP), COP was sampled at 750 Hz with a dual-platform arrangement (AMTI OR6 2000, Newton, MA). Preferred standing position for individual subjects, corresponding to foot width and angle, was recorded on the force platform to ensure the physical support was consistent between trials and conditions. Motion capture was performed with 10 VICON$^{\text{TM}}$ T-40 cameras sampled at 750 Hz with the Nexus software (Vicon$^{®}$ Motion Systems, Lake Forest, CA). Data were collected in a single session (~30 min). Five 30 s trials were collected in each of six conditions.

Procedure

Subjects balanced a 62 cm long, 0.65 cm wide, and 50 g mass wooden dowel on their index finger. Reflective spherical markers (14 mm) were affixed to the top and bottom of the dowel for kinematic capture.

There were six experimental conditions: (1) Posture condition (P): postural fluctuations were determined from five quiet standing trials (30 s). Participants did not receive explicit attentional instructions for the P condition (e.g., minimize sway, be as still as possible). (2) The Posture-Cognitive Dual-Task (P-CDT) condition required subjects perform six serial arithmetic operations (addition, subtraction), one computation per five-second interval while maintaining upright stance. Subjects were given a number between 0 and 100 before each trial. At trial onset, a sequence of integer operations was performed over five-second intervals according to the method of Weeks et al. (2003). Arithmetic operations were performed silently, with the final response verbalized following trial completion. (3) Subjects balanced the stick in upright stance without attentional instructions for balancing (P-SB). This condition served as our attentional control for stick balancing. (4) In the Posture-Stick Balancing External focus condition (P-SBEXT), subjects were instructed to 'minimize deviations of the stick from the vertical'. (5) In contrast, subjects were instructed to 'focus on minimizing hand and finger movement' prior to each trial in the Posture-Stick Balancing Internal focus condition (P-SBINT). Attentional instructions for P-SBEXT and P-SBINT conditions resembled those implemented by Wulf et al. (2004). (6) The influence of the Posture-Cognitive Dual-Task on stick balancing dynamics was determined through the outlined arithmetic task (P-SB-CDT).

Task difficulty was conserved between P-CDT and P-SB-CDT conditions by preserving integer operations. However, for the CDT condition, subjects began with the initial number from a P-SB-CDT trial, with the order of operations randomized. Randomizing the sequence of integer operations served to minimize learning of the cognitive task between conditions. An example series for the P-SB-CDT condition follows: 40 (before trial) + 5 (trial onset) − 7 (5 s) + 4 (10 s) + 8 (15 s) − 3 (20 s) − 9 (25 s) = 38 (30 + s). A randomized sequence for the P-CDT condition was 40 (before trial) + 8 (trial onset) + 4 (5 s) − 7 (10 s) − 9 (15 s) + 5 (20 s) − 3 (25 s) = 38 (30 + s).

We implemented a silent arithmetic paradigm to minimize articulatory confounds on postural dynamics (Yardley et al. 1999). Subjects were allotted a break (~30 s) between trials. If the trial was not completed, the data were excluded from analysis and the trial was repeated. The P-SB condition was performed first to prevent confounds resulting from attentional instructions for balancing. Remaining conditions were block-randomized with MATLAB$^{\text{TM}}$ (Mathworks, Natick, MA), constituting a pseudorandomized block design.

The statistical stability of performance was determined by root-mean-squared (RMS) variability of transverse plane COP and FINGER trajectories. RMS COP was contrasted between postural (marginal mean; P & P-CDT) and stick balancing conditions (marginal mean; P-SB, P-SBEXT, P-SBINT, P-SB-CDT) (*t*-test, two-tailed) to quantify the magnitude of postural variability attributable to stick balancing. One-way (4 levels: P-SB, P-SBINT, P-SBEXT, P-SB-CDT) analysis of variance (ANOVA) with repeated measures determined attentional and cognitive influences on COP and FINGER trajectories for stick balancing. Huynh–Feldt corrections were employed for sphericity violations (Mauchly's Test, $P < .05$). RMS FINGER magnitude was subjected to one-way (4 levels: P-SB, P-SBINT, P-SBEXT, P-SB-CDT) ANOVA with repeated measures. COP and FINGER trajectories were resampled by a non-overlapping 10 sample moving average, resulting in an effective sampling rate of 75 Hz for numerical analysis.

The power spectral density (PSD) of planar fingertip and COP trajectories was computed for individual trials by Welch periodogram with a non-overlapping Hamming window. The mean power frequency (MPF) of COP and FINGER trajectories was determined by weighted average from the PSD, ensemble averaged for each condition and subjected to the outlined statistical analyses.

Stabilogram-diffusion analysis was performed on planar COP and FINGER increments according to the method of Collins and De Luca (1994). COP and FINGER trajectories were considered two-dimensional random walks, defined by mediolateral and anteroposterior deviations. The two-point correlation function for planar stabilograms, $K(\tau)$, was computed for the lag τ on [0.1, 10] s by

$$K(\tau) = \frac{1}{N-m}\sum_{i=1}^{N-m}\left[(x(t)-x(t+\tau))^2 + (y(t)-y(t+\tau))^2\right], \tag{1}$$

where $t = i\Delta t$ and $\tau = j\Delta t$.

The critical time (τ_c) was defined as the first instance the Hurst exponent crossed $H = 0.5$. Critical times were determined for individual subjects from ensemble-averaged stabilogram-diffusion plots for each condition. The critical time, τ_c, defines the boundary between persistent (positively correlated, $H_s > 0.5$) and anti-persistent (negatively correlated, $H_l < 0.5$) dynamical regimes. A linear regression was applied to the double-logarithmic plots of K (τ) COP and $K(\tau)$ FINGER versus τ on $[0.1, \tau_c)$ and $(\tau_c, 10]$ s. Best-fit short- and long-range scaling exponents were divided by 2 for fractional Brownian motion, to render H_s and H_l.

The linear cross-correlation function was computed between COP and FINGER positions for a representative subject. COP and FINGER time series were normalized on the interval $[-1, 1]$. The cross-correlation function $z(\tau)$ was computed for transverse plane COP and fingertip trajectories for the lag τ on [0, 3] s.

Results

Figure 1 shows representative COP and FINGER time series for a single subject in the stick balancing external focus condition (P-SBEXT). Transverse plane COP (Fig. 1a) and FINGER (Fig. 1b) stabilograms depict mediolateral (ML; abscissa) relative to anteroposterior (AP; ordinate) positions. The corresponding AP and ML COP (Fig. 1c, d) and FINGER time series (Fig. 1e, f) are depicted in the right column subplots. Transverse plane FINGER and COP position series are irregular and nonstationary for the displayed 30 s interval. The following results were determined from transverse plane stabilograms (Fig. 1a, b).

Variability analysis

Sway variability was influenced by balancing condition [F (1.82, 16.39) = 5.85, $P < 0.05$, $\eta^2 = 0.39$], as shown in Fig. 2a. Explicit attentional focus did not influence sway magnitude (RMS COP), since spontaneous sway was similar between P-SBEXT and P-SBINT conditions ($P > 0.05$). However, sway variability was reduced by conjoint cognitive and postural-stick balancing performance. In that regard, RMS COP was reduced in P-SB-CDT relative to P-SB ($P < 0.05$), P-SBEXT ($P < 0.05$) and P-SBINT ($P < 0.01$) conditions. The variability of fingertip trajectories RMS FINGER was also dependent on attentional instruction [F (3, 27) = 27.95, $P < 0.001$, $\eta^2 = 0.76$] (Fig. 2b). Fingertip displacements were least variable when performing the concurrent cognitive, postural and stick balancing task (P-SB-CDT; $P < 0.05$) and most variable in the P-SBINT condition ($P < 0.05$).

Stabilogram-diffusion analysis

A representative subject, ensemble-averaged stabilogram-diffusion plot is depicted in Fig. 3 for postural (a) and fingertip (b) components of the stick balancing task. Figure 3 shows qualitative differences for the short-range scaling region and critical time (inflection) between incremental changes in COP (a) and FINGER (b) series across balancing conditions. In contrast, the long-range scaling region was qualitatively similar for $\tau > 1$ s.

The short-range scaling exponent for COP displacements, H_s COP, was influenced by condition [F (5, 45) = 2.99, $P < 0.05$, $\eta^2 = 0.25$]. Corresponding summary statistics are presented in Fig. 4a. H_s COP was reduced in the

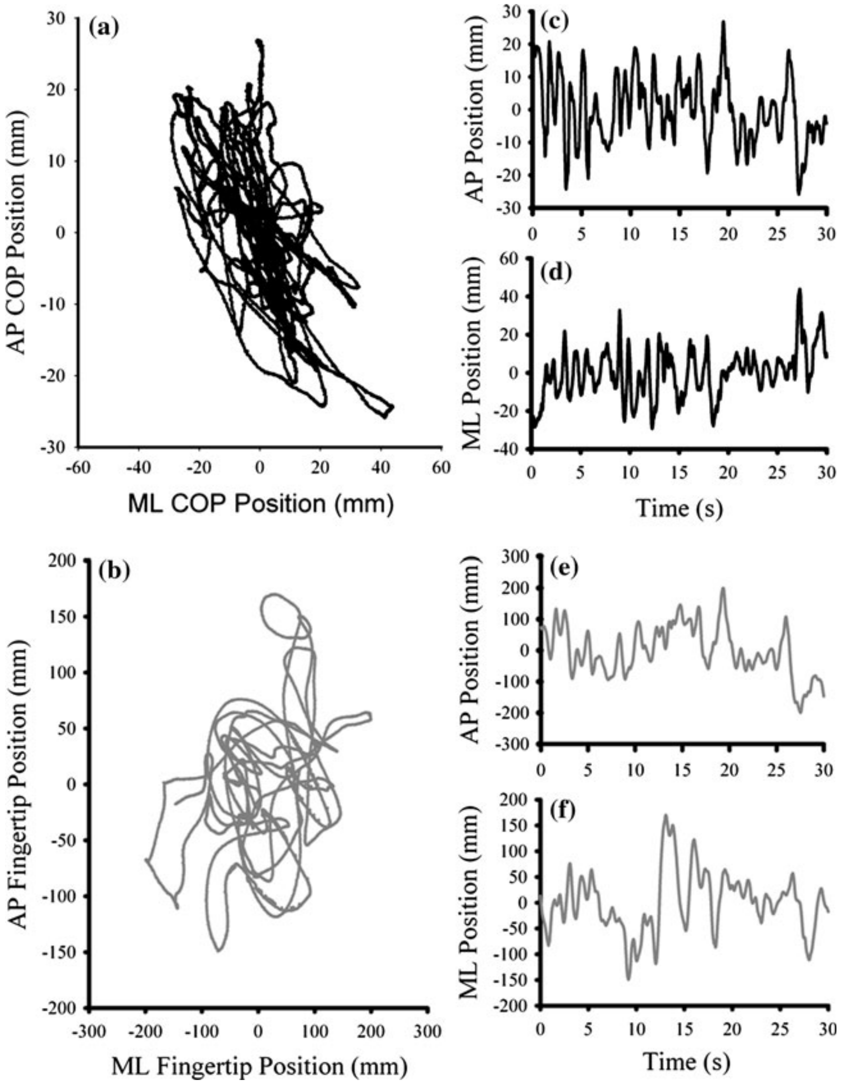

Fig. 1 Representative COP and FINGER position series for a single subject in the stick balancing external focus condition (P-SBEXT). **a** COP and **b** Finger stabilograms depicting mediolateral (ML; abscissa) relative to anteroposterior (AP; ordinate) positions. **c** AP COP, **d** ML COP, **e** AP fingertip and **f** ML fingertip position (mm) time series. Transverse plane Finger and COP position series are irregular and non-stationary for the displayed 30-s interval

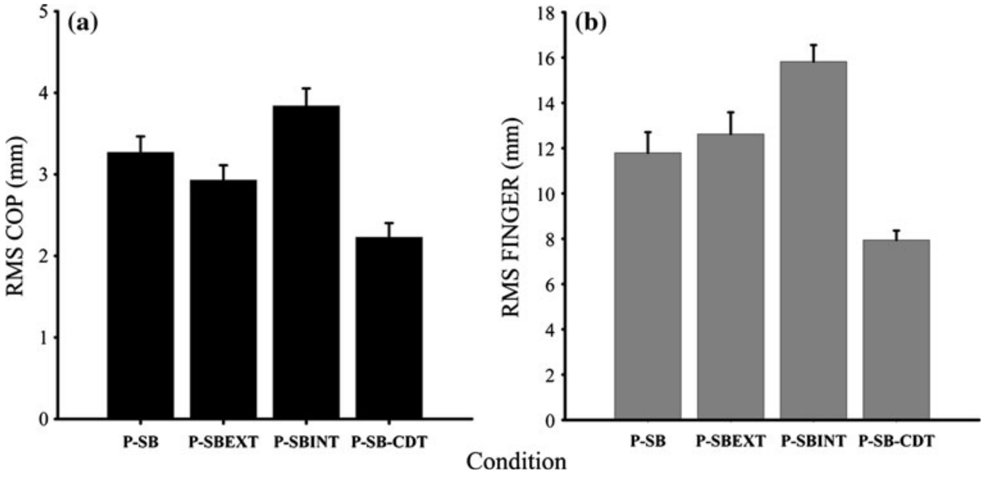

Fig. 2 The statistical stability of postural and suprapostural performance is dependent on focus of attention for balancing. COP and fingertip trajectories were least variable when stick balancing was performed with a concomitant cognitive load. **a** RMS COP and **b** RMS FINGER were reduced in the stick balancing cognitive dual-task condition (P-SB-CDT). Of particular interest was the stabilizing effect of cognitive load for stick balancing performance. Finger trajectories were approximately half as variable in P-SB-CDT relative to other conditions. *Error bars* represent ±1 standard error of the mean (SEM)

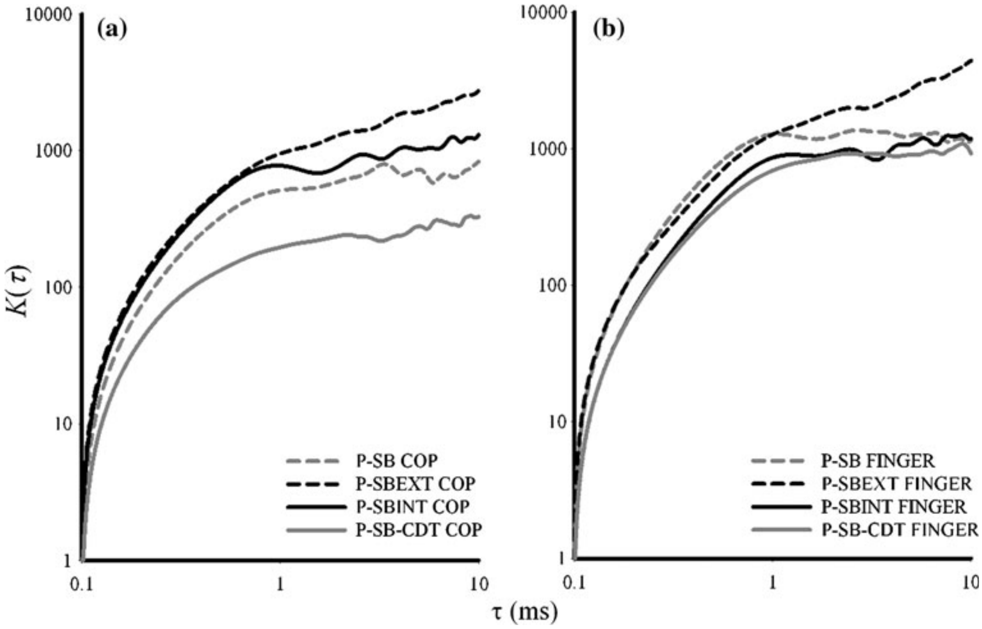

Fig. 3 Double-logarithmic stabilogram-diffusion plots depicting a single subject, ensemble-averaged two-point correlation function ($K(\tau)$) versus the time between observations (τ) for experimental focus of attention conditions **a** COP and **b** FINGER time series. Incremental changes in COP and FINGER position showed two distinct scaling regions in stick balancing. Stabilogram-diffusion analysis showed short- (H_s) and long-range (H_l) scaling regimes, which characterize temporally distinct persistent (drift) and anti-persistent (corrective) dynamical regimes separated by the critical time (τ_c)

stick balancing (marginal mean; $H_s = 0.61$) relative to P and P-CDT (marginal mean; $H_s = 0.69$) conditions ($P < 0.05$). COP displacements were less persistent when stick balancing, which amounts to more stationary postural deviations. H_s FINGER was also dependent on condition [F (3, 27) = 7.48, $P < 0.001$, $\eta^2 = 0.45$], as shown in Fig. 4d. H_s FINGER was similar between P-SB, P-SBEXT and P-SBINT conditions ($P > 0.05$). Cognitive load (P-SB-CDT) reduced the magnitude of serial correlation in fingertip trajectories ($P < 0.05$).

The long-range scaling (Fig. 4b) exponent for incremental changes in COP position, H_l COP, was greater for the postural and postural-cognitive dual-task (P, P-CDT; $H_l = 0.24$) relative to balancing conditions (P-SB, P-SBEXT, P-SBINT, P-SB-CDT; $H_l = 0.11$) ($P < 0.01$). Therefore, the stringency of COP corrective displacements increased when stick balancing. H_l FINGER (Fig. 4e) was not influenced by the condition [F (3, 27) = 0.66, $P > 0.05$, $\eta^2 = 0.07$].

Critical time for switching postural regimes (τ_c COP) was not dependent on attentional focus for balancing, [F (3, 27) = 0.25, $P > 0.05$, $\eta^2 = 0.03$]. Critical times for switching between drifting and corrective postural regimes were similar for P-SB, P-SBEXT, P-SBINT and P-SB-CDT conditions. However, τ_c COP was reduced in the P and P-CDT (marginal mean; τ_c COP = 0.44 s) relative to stick balancing conditions (marginal mean; τ_c COP = 0.74 s) (t-test, one-tailed, $P < 0.05$). Critical time for switching fingertip regimes, τ_c FINGER (Fig. 5), was dependent on condition [F (3, 27) = 3.22, $P < 0.05$, $\eta^2 = 0.27$]. τ_c FINGER was reduced in the P-SB and P-SB-CDT relative to P-SBINT ($P < 0.05$) and P-SBEXT ($P < 0.05$) conditions. Consequently, critical times were reduced when the attentional focus was non-specific (P-SB) and external, but task-irrelevant (P-SB-CDT).

Surrogate series were computed by phase-randomized COP and FINGER increments (Theiler et al. 1992). The two-point correlation function, $K(\tau)$, was computed for surrogate series to determine whether computed correlations were artifact of series length, or the distribution and amplitude of increments. Linear regression on the double-logarithmic stabilogram-diffusion plot on $\tau \in [0, 10]$ s revealed a single scaling region for the phase-randomized COP (Fig. 4c) and FINGER (Fig. 4f) displacement series, $H_{\text{surrogate}} \approx 0.5$, rendering increments equivalent to classical Brownian motion. Computed short- and long-range scaling regimes and critical times therefore reflected temporally distinct dynamical regimes.

Spectral analysis

The mean power frequency (MPF) of transverse plane COP displacements was dependent on balancing condition [F (1.91, 17.22) = 28.184, $P < 0.001$]. Summary statistics are depicted in Fig. 6. MPF COP was reduced in P ($P < 0.01$) and P-CDT relative to stick balancing conditions ($P < 0.01$), suggesting the spectral composition of COP time series was increased for the balancing task. MPF COP was greater in the P-SB and P-SBINT conditions relative to P-SB-CDT ($P < 0.001$), reflecting higher frequency components. MPF COP was similar for the P-SBEXT and P-SB-CDT ($P > 0.05$). MPF FINGER was also dependent on stick balancing condition [F (1.82, 16.40) = 4.51, $P < 0.05$, $\eta^2 = 0.33$]. MPF was reduced in

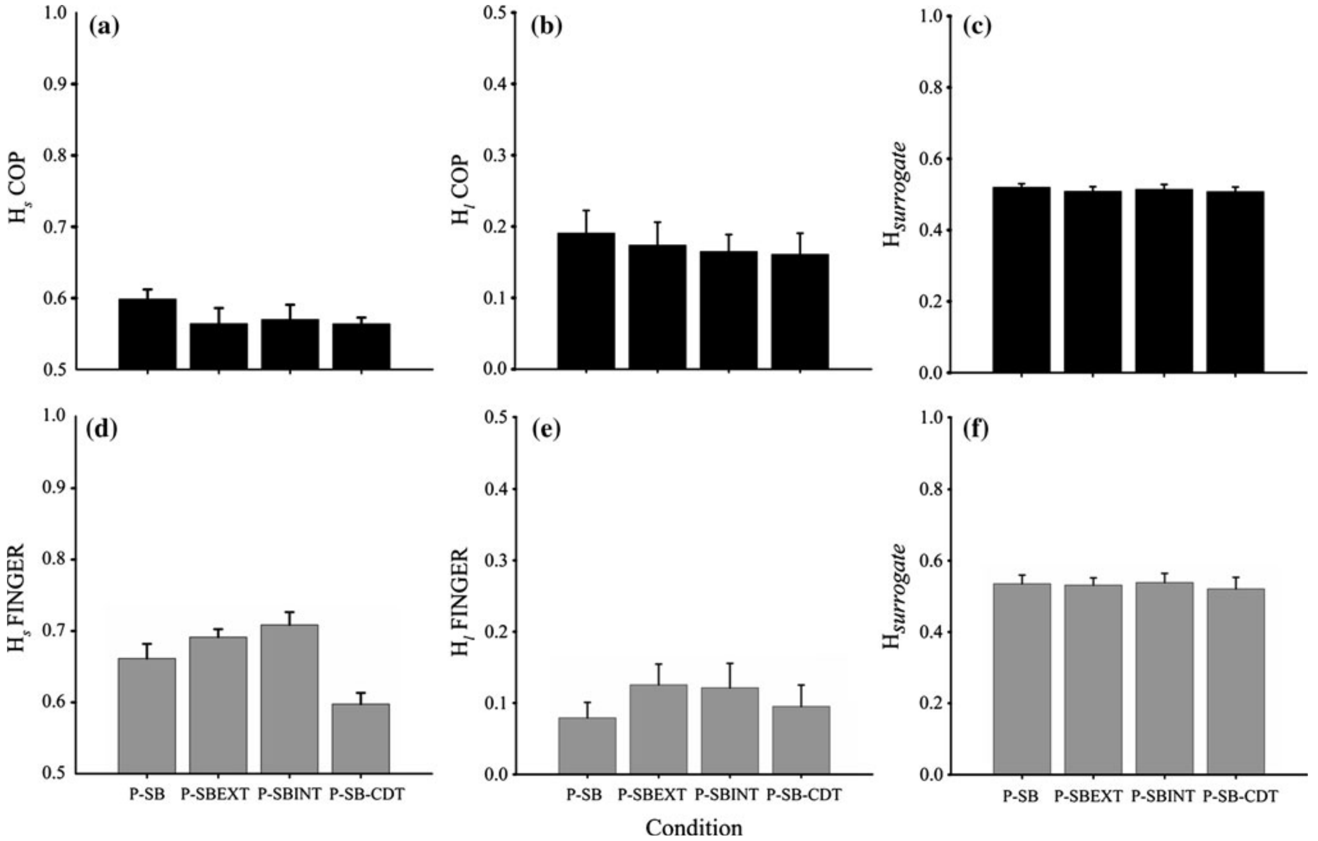

Fig. 4 Short- (H_s) and long-range (H_l) scaling exponents revealed two distinct timescales for postural and stick balancing position series. **a** Short- (H_s) and **b** long-range (H_l) postural scaling exponents. **d** Short- and **e** long-range stick balancing scaling exponents. For short intervals, incremental changes in COP and FINGER position were positively correlated (persistent), but negatively correlated for long intervals (anti-persistent). H_s was reduced for FINGER trajectories in the stick balancing dual-task condition (P-SB-CDT), resulting in more stationary series. Surrogate analysis for both COP and FINGER trajectories was similar to classic Brownian motion ($H \approx 0.5$). *Error bars* represent ± 1 SEM

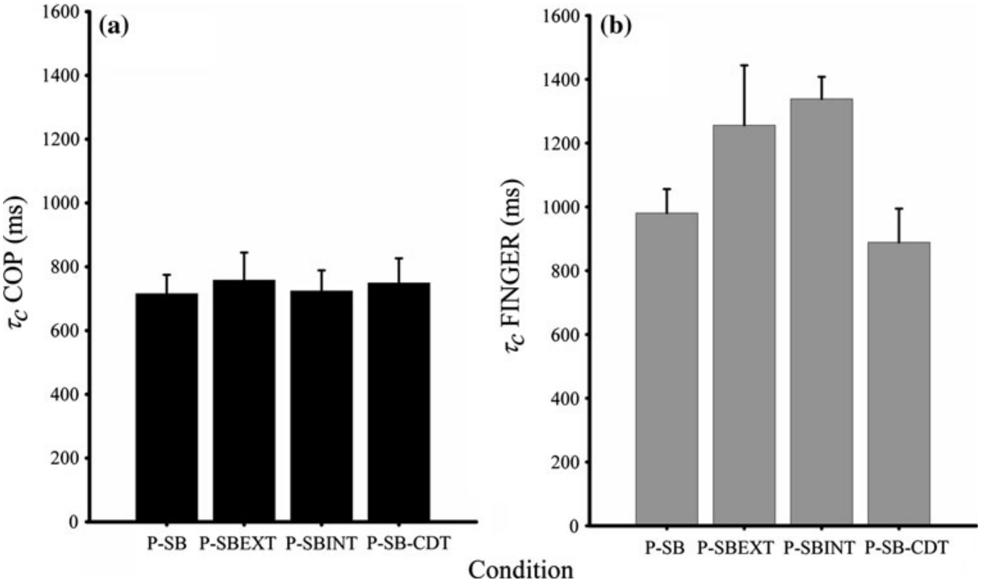

Fig. 5 The critical time (τ_c) for switching between **a** postural (COP) and **b** stick balancing (FINGER) regimes. Critical times for switching postural regimes were increased for stick balancing relative to stance (P) and dual-task postural condition (P-CDT). Critical times were similar between P and CDT conditions. In contrast, the critical time for switching between FINGER regimes was reduced in the stick balancing cognitive task condition (P-SB-CDT). *Error bars* represent ±1 SEM

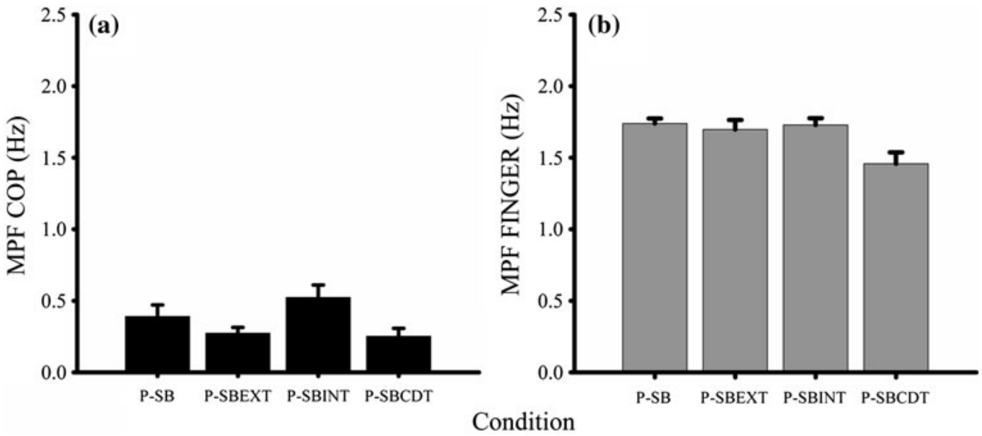

Fig. 6 Statistical summary for the spectral decomposition of COP and fingertip displacement time series. **a** The mean power frequency (MPF) of COP trajectories was reduced in quiet stance relative to stick balancing conditions and in the stick balancing dual-task relative to control (P-SB) and attentional focus conditions (P-SBEXT, P-SBINT). The MPF of COP trajectories was reduced in P, P-CDT relative to suprapostural conditions. **b** The MPF of FINGER trajectories was reduced in the stick balancing dual-task condition (P-SB-CDT) relative to control (P-SB) and focus of attention conditions (P-SBEXT, P-SBINT). *Error bars* represent ±1 SEM

the P-SB-CDT relative to P-SB ($P < 0.01$), P-SBINT ($P < 0.05$) and P-SBEXT ($P < 0.05$) conditions.

Linear cross-correlation analysis

Figure 7 demonstrates that the experimental manipulation evoked differences in the dynamical relationship between COP and FINGER positions. For the P-SBEXT condition, COP and finger position were negatively correlated for lags $\tau \in [0,\ 1.5]$ s, suggesting that COP lagged FINGER position. The externalized focus whereby individuals focused on stick position with respect to the vertical produced compensatory COP displacement over longer intervals $\tau \in [1.5,\ 3]$ s. In contrast, COP and FINGER position were positively correlated for lags $\tau \in [0, 3]$ s in the P-SB, P-SBINT and P-SB-CDT conditions. Positively correlated trajectories demonstrate that FINGER and COP followed the same spatiotemporal pattern. The externalized focus, therefore, saw the emergence of a distinct postural–suprapostural dynamic.

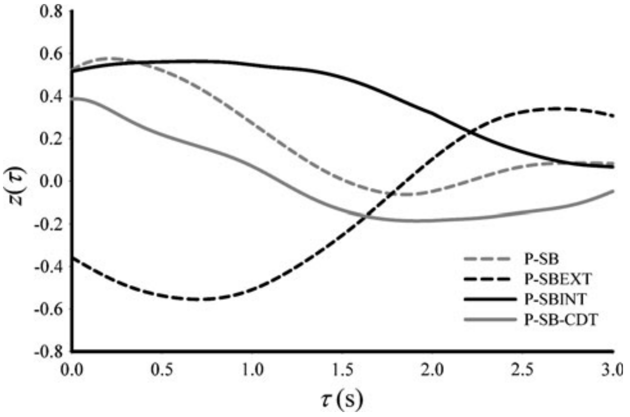

Fig. 7 Ensemble-averaged cross-correlation function $z(\tau)$ between COP and FINGER positions for a representative subject. The cross-correlation function $z(\tau)$ was computed for transverse plane, normalized COP and FINGER trajectories and is plotted for lag τ on the interval [0, 3] s. The experimental manipulation evoked differences in the dynamical relationship between COP and FINGER position. COP and FINGER position were negatively correlated in the P-SBEXT condition for lags $\tau \in [0,\ 1.5]$ s, suggesting that COP lagged FINGER position. For the externalized focus condition, individuals focused on stick position with respect to the vertical. Compensatory COP displacements were produced over longer intervals $\tau \in [1.5,\ 3]$ s. In contrast, COP and FINGER position were positively correlated for lags $\tau \in [0, 3]$ s in the P-SB, P-SBINT and P-SB-CDT conditions. Positively correlated trajectories demonstrate that relative FINGER and COP displacements were in the same direction. The externalized focus, therefore, P-SBEXT saw the emergence of a distinct postural–suprapostural temporal dynamic

Discussion

Stick balancing dynamics

The purpose of this study was to determine the dynamical influence of different attentional foci on postural (COP) and suprapostural (fingertip) components of human stick balancing. We sought to determine whether two variants of an external focus of attention, task-relevant (P-SBEXT) and task-irrelevant (P-SB-CDT) increased the stability of center of pressure and fingertip series. In the task-relevant external focus, participants were instructed to focus on displacement of the stick from the vertical. In contrast, for the task-irrelevant external focus (P-SB-CDT), participants performed a serial arithmetic task while stick balancing. In addition to summary statistics (RMS variability), we analyzed the

COP and fingertip trajectories by method of spectral analysis and statistical mechanics (Rougier 2008).

We hypothesized that both postural and suprapostural components of the stick balancing task would be stabilized by a task-irrelevant external focus of attention (P-SB-CDT). We predicted that an internal focus of attention would compromise dynamical stability in the stick balancing task, resulting in variable COP and FINGER trajectories. In confirmation of the hypothesis, FINGER and COP trajectories were least variable when participants partitioned attentional resources between stick balancing and cognitive task components, corresponding to an external, task-irrelevant focus (P-SB-CDT). In contrast, COP and FINGER displacements were least stable when the focus of attention was internal. Performance stability for the external, task-relevant condition was similar to control performance (P-SB).

The stochastic nature of human stick balancing has been discussed at length. Studies suggest that control for stick balancing is performed according to a drift and correct (Milton et al. 2009b) mechanism that reflects scale-invariant properties of the central nervous system (Werner 2009). The proposed mechanism consists of small, correlated incremental changes in fingertip position, interspersed with corrective, negatively correlated displacements.

In accordance with the intermittent drift and correct mechanism, stabilogram-diffusion analysis demonstrated that incremental changes in fingertip (FINGER) position occur on distinct timescales. For short intervals ($\tau < \tau_c$), incremental changes in fingertip position are positively correlated. Positive, serially correlated increments imply that sensorimotor control is open-loop, i.e., the finger tends away from relative equilibrium. In contrast, for long timescales ($\tau > \tau_c$), incremental changes in fingertip position reflect closed-loop sensorimotor control where the finger tends to relative equilibrium.

A novel contribution of this study was the observed influence of attentional manipulation on fingertip dynamics. The magnitude of correlation for short intervals (H_s FINGER) was similar regardless of whether attention was internal or external, task-relevant. However, for the external, task-irrelevant focus (P-SB-CDT), cognitive load reduced the magnitude of short-range serial correlation, which defines the stochasticity of fingertip displacement in terms of jump amplitude and frequency (Mandelbrot and van Ness 1968). Reduced persistence in series was accompanied by decreased critical time for switching between open- and closed-loop balancing regimes, τ_c FINGER for the external, task-irrelevant condition. In effect, reduced persistence in series and shorter time for switching regimes amounted to a more stationary process when attentional focus was external and irrelevant to task performance (P-SB-CDT). This result corroborates our result for time series variability, where RMS variability was reduced when the focus for balancing was external and task-irrelevant (P-SB-CDT).

The lack of difference in the long-scale Hurst exponent establishes that a similar corrective process was employed for stick balancing, regardless of focus of attention. This result likely reflects the permissible range of upper limb deviation or 'dead zone' for thresholded deviations (cf. Collins and De Luca 1994; Milton et al. 2009c). Non-linear models, as mentioned earlier, have been implemented for postural control (Milton et al. 2009a, b, c) and a manual, stance-controlled inverted pendulum task (Lakie and Loram 2006). Our data suggest the dynamical threshold for fingertip displacements changes as a function of attentional foci. Participants correct with similar stringency when the permissible range of motion is exceeded. At present, we do not understand the extent to which the deviation threshold of the hand represents upper limb biomechanics (range of motion), sensory or central components (Mergner et al. 2001).

The mean power frequency of displacements was reduced in P-SB-CDT relative to all other conditions and reflects a slower dynamic. Fingertip dynamics for stick balancing were characterized by reduced frequency, reduced amplitude displacement with incremental changes in position that were only weakly correlated over short timescales for the external focus task-irrelevant condition. Regardless of attentional condition, long-range correlations were very anti-persistent.

These results do not directly support the constrained action theory for motor performance (Wulf et al. 2004). Specifically, this theory predicts decreased variability, increased frequency components when the focus of attention is external and task-relevant, and increased variability, reduced frequency dynamics when attentional focus is internal. Though cross-correlation analysis demonstrated that a different dynamical relationship was evoked by the external, task-relevant focus, our data were inconsistent with the above predictions. This might represent task familiarity of our participants and subsequent melding of the perceptual boundary to accommodate the balanced stick. This phenomenon, commonly referred to as exproprioception, is extensively documented (Maravita et al. 2002; 2003). It is important to consider the role of exproprioception with respect to constrained action theory. In studies that reported enhanced learning with external focus, the external/internal focus duality was established early in the learning process (McNevin et al. 2003). Additionally, most of the work related to the constrained action theory has dealt with tasks where the line between the actor and a tool being controlled is fairly clearly defined. Hence, manipulations of attentional focus did not have to deal with issues of exproprioception.

Future work should examine this issue in the context of the interplay between task familiarity, attentional focus and performance.

That performance was facilitated by the cognitive task that corroborates the stabilizing effect of external, task-irrelevant focus for performance (Weeks et al. 2003). The benefit of task-irrelevant focus is further supported by literature regarding sensorimotor expertise (Milton et al. 2008b; Beilock et al. 2002). Less experienced balancers are unlikely to benefit from an external, task-irrelevant focus (Milton et al. 2008b).

Postural dynamics

COP displacements were more variable and reflected higher frequency components when stick balancing. In addition, the relative scaling of postural regimes was influenced by the stick balancing task. COP displacements were less correlated over short, but more correlated for long intervals when stick balancing. Critical times for switching between short- and long-range postural regimes increased when stick balancing but were similar regardless of attentional condition. Postural corrections were therefore performed at longer timescales when stick balancing. For a given serial correlation, if the system drifts for prolonged time, the tendency is to migrate toward the support boundary. Corrective movements, when performed, prevent destabilization resulting from the COP traversing the base of support. When stick balancing, critical times increased and translated to a concomitant increase in the degree of anti-persistence. The degree of anti-persistence observed for COP increments in stick balancing ($0 < H_l < < 0.5$) approaches the scaling exponent to be expected if the support boundary had been attained ($H_l \approx 0$; Collins and De Luca 1994). These results are consistent with the facilitatory viewpoint of posture, which considers sway subservient to supraordinate task performance (Stoffregen et al. 1999). Our results, therefore, recapitulate the importance of context in the optimal assembly of postural synergy (Balasubramaniam and Turvey 2000; Todorov and Jordan 2002).

We did not observe differences in postural dynamics when performing a cognitive dual task (P-CDT). This effect is not surprising, since postural control in healthy individuals is robust to secondary cognitive demand (Dault et al. 2001), and the efficiency of resource allocation to postural and cognitive task components reflects several factors. Consequently, perturbed (Pellecchia 2003), stabilized (Andersson et al. 2002) and unaffected (Dault et al. 2001) stability have been reported in dual-task paradigms. In this experiment, participants performed a silent arithmetic task in a stable, well-learned postural context. Consequently, the neural pathways subservient to balance were likely relegated to low-level reflexive and compensatory mechanisms (Torres-Oveido et al. 2006) and central interference was minimized.

In our experience (Cluff and Balasubramaniam 2009; Cluff et al. 2009), three strategies are typical of experienced stick balancers. Proficient stick balancers position the hand so that it is either possible to see both the tip of the stick and hand simultaneously or, conversely, the hand is positioned sufficiently close to the body that it is possible to see only the tip of the stick. An intermediary strategy reflects a combination of the two. An elaborate methodology would be required to assess eye–hand coordination in stick balancing of the type outlined in Hayhoe and Ballard (2005) and is a subject for future research. We are confident, however, that our results reflect attentionally mediated task dynamics and not a generalized inability to maintain instructed attentional foci. Figure 7 shows a representative, ensemble-averaged cross-correlation function between radial COP and finger position for P-SB, P-SBEXT, P-SBINT and P-SB-CDT conditions. That COP and finger position were negatively correlated for lags $\tau \in [0,\ 1.5]$ s suggests the COP lagged fingertip displacement—individuals focused on stick movement with respect to the vertical and produced compensatory COP movement over longer intervals $\tau \in [1.5,\ 3]$ s. Conversely, for P-SB, P-SBINT and P-SB-CDT conditions, COP and fingertip position were positively correlated for lags $\tau \in [0, 3]$ s, which suggests that finger and COP displacement paralleled one another. Consequently, the external focus, task-relevant condition saw the emergence of a balancing strategy that prioritized stick movement.

It is important to consider focus of attention in the context of Bernstein's ideas on expertise and its development (see Latash and Turvey 1996 for a review). While actors focus on moving body parts in the early stages of skill acquisition, attention shifts to wielded objects in advanced stages of skill (Bernstein 1967). Advanced tennis players tend to focus on the ball or end point of the trajectory for a successful return, rather than the racquet or limb. In the stick balancing case, there is no clear boundary between where one ends and the other begins. A possible reason that attention manipulation did not reveal differences between the internal and external, task-relevant condition might reflect that the stick becomes an extension of the body as one acquires expertise (Maravita et al. 2003). Therefore, it is likely that stick balancers at earlier stages of skill acquisition show stronger differences as a function of attentional focus. We are currently exploring skill acquisition in stick balancing and its relationship to postural dynamics.

Acknowledgments This work was supported by an NSERC Discovery grant and a CRC awarded to the last author. The first author was supported by an NSERC Alexander Graham Bell Canada Graduate scholarship. We wish to thank Jason Boulet and two anonymous reviewers for comments that helped improve this manuscript.

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