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Swaying to the complex motion of a visual target affects postural sway variability

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Abstract

Background

Voluntary shifting body weight in the anteroposterior direction is an important element of daily life activities, such as rising from a chair or initiating a step. In order to accommodate the daily-life challenges of such tasks, voluntary postural sway needs to be flexible and variable.

Research question

In this study we asked how whole-body tracking of a complex visual target motion with the concurrent provision of feedback modulates the variability of voluntary sway.

Methods

Twenty young adults (age: 27.10 ± 9.15 years, height: 170.73 ± 9.40 cm, mass: 62.84 ± 11.48 kg) performed 132 cycles of voluntary antero-posterior sway, on a force platform, under two conditions: a) self-paced sway and b) swaying while tracking the complex motion of a visual target. Magnitude and temporal structure of variability of postural sway were investigated with the Coefficient of Variance (CoV) and the fractal exponent α, respectively. This analysis was performed for sway cycle duration, amplitude and velocity. The cross-correlation function between the target and sway cycle parameters was computed as a measure of visuo-postural coupling.

Results

The CoV of sway cycle amplitude, duration and velocity increased during active tracking of the complex target. Fractal exponent α increased for sway cycle amplitude but

decreased for cycle duration and remained unchanged for sway velocity. The cross-correlation function revealed a consistent peak at lag+1 indicating an asynchrony between the target and sway cycle duration, while the peak cross-correlation for cycle amplitude was noted at lag 0.

Significance

Swaying to the complex motion of a visual target improves the variability of sway cycle amplitude, at the cost of cycle duration. This is associated with a more synchronous spatial than temporal coupling to the visual target motion. This knowledge could inform the design of postural tracking paradigms as appropriate exercise interventions, for improving voluntary sway in populations with reduced limits of stability (i.e. older adults).

1. Introduction

When humans perform the same task multiple times, it is never executed the same way. These natural fluctuations in motor performance define the presence of human movement variability which is ubiquitous in all biological systems and necessary for the successful interaction with the ever changing environment [1]. How variability is structured over time has been widely studied in cyclical activities such as walking showing that stride length and duration exhibit, over time, a degree of *persistency* [2,3]. In sense, when increases in variations of consecutive strides are followed by decreases, the walking pattern is characterized as *anti-persistent* because the direction of change in variations does not persist in time. The opposite is true in *persistent* behavior where increases are followed by increases and decreases by decreases [4]. The *persistent* pattern of variations constitutes a landmark of healthy movement; on the contrary, divergence from this state occurs due to aging or disease [5]. Particularly, decreased postural sway persistency is associated with impaired balance control in aging [6] while decreased walking persistency is related to falls [7].

Synchronizing heel-strikes to the beeps of a persistent metronome during walking, modulates the persistency of stride duration [[8], [9], [10]]. This modulation is stronger when the current walking cycle couples to the current metronome interval. By contrast, the modulation is weaker when the current walking cycle synchronizes to the previous metronome interval, revealing an asynchrony between the metronome and the cyclic task [11]. Although modulating stride persistency using complex metronomes has been widely studied in walking, little is known about whether similar modulations could be obtained when voluntarily tracking a complex visual target motion using postural sway, a visuo-motor task paradigm that is used as balance rehabilitation exercise [12].
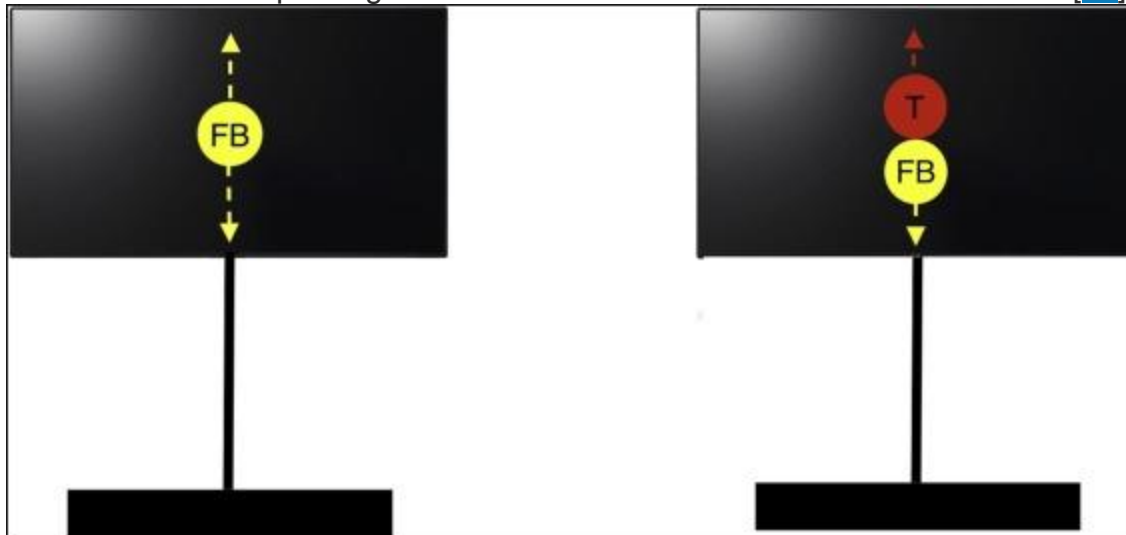

Fig. 1. Participants shifted their bodyweight antero-posteriorly, in front of the screen, watching either one yellow dot (feedback of CoP) (SELF, left) or two dots: a yellow representing feedback and a red representing the persistent visual target to be tracked (PINK, right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Voluntary weight shifting in the antero-posterior direction (postural sway) is an important element of many daily activities such as rising from a chair, initiating gait or compensating the inertial effect of a segment movement such as arm throwing or kicking a ball. While swaying, any unexpected shift of the center of mass close or over the spatial limits of the base of support may lead to an unbalanced situation or even a fall [13]. In order to enhance the spatial control of the task, balance rehabilitation protocols have used voluntary postural sway while tracking moving visual targets with concurrent provision of performance feedback [12,14,15]. Visuo-postural tracking paradigms are based on our current knowledge that humans, independent of age, can

couple their voluntary sway to a visual target, which moves in a non-variable fashion [16]. However, the results of balance interventions using such non-variable stimuli, have shown that the acquired adaptations neither last [17], nor transfer to other motor tasks [18]. The lack of retention and transferability may be due to the employment of feedforward control when postural sway is coupled to non-variable visual targets. Nevertheless, in every-day life, interaction with the dynamically changing world demands variable actions that are capable of dealing with the uncertainty of the environment [1,19]. Recent work from our laboratory shows that young adults can couple their voluntary sway to the complex motion of a visual target with the same ease they couple to a non-variable/periodic one [20,21]. What is not known however, is whether coupling postural sway to the complex motion of a visual target modulates variability in terms of both magnitude (i.e. measures of variance) and temporal structure (i.e. persistency).

Based on the above, the aim of the current study is to investigate how swaying to the complex motion of a visual target affects the magnitude and temporal structure of voluntary sway variability. We investigated these parameters for sway cycle amplitude, duration and velocity and examined the origin of any potential modulations by evaluating the coupling to the target's cycle amplitude and duration respectively. We hypothesized that a) tracking of a complex target will affect the variability and persistency of voluntary postural sway and b) these effects would be the result of both spatial and temporal coupling to the visual target motion.

2. Methods

2.1. Participants

Twenty young adults, recruited among University students (age: 27.10 ± 9.15years, height: 170.73 ± 9.40 cm, mass: 62.84 ± 11.48 kg). All participants were healthy with no history of neuromuscular impairments and had normal or corrected to normal vision. Participants were informed about the experimental protocol and gave their consent prior to their inclusion in the study. The experiment was performed with the approval of our institution's ethics review committee in accordance with the Declaration of Helsinki.

2.2. Apparatus, task and stimuli

Participants stood on a force platform (Balance Plate 6501, Bertec, USA, sampling rate: 100 Hz), with an inter-malleolar distance corresponding to the 10 % of their height for the acquirement of Center of Pressure (CoP). A TV screen (LG 60LA620S-ZA, 60 in.) was positioned 1.5 m in front of them and centered at eye level.

The experiment was performed in two sessions. In the first session participants performed 132 cycles of voluntary antero-posterior (AP) postural sway (i.e. heel to toe rhythmic rocking) at their self-selected pace, while receiving feedback of the AP movement of their CoP, represented by a vertically moving dot projected on the screen [20,21]. This was required to identify the individual sway cycle duration and amplitude in the first session. This information was used to normalize the motion of the visual target to the individual's amplitude (normalized to foot-length) and frequency boundaries. In the second session, performed a week later, participants were again instructed to rhythmically sway for 132 cycles in the AP direction, exactly as described in the 1st session, under 2 conditions: a) voluntary self-paced sway with provision of CoP feedback (SELF), and b) rhythmic sway guided by a simulated target, created to be unpredictable, using a target that was constructed using statistical properties sourced from pink noise (PINK). Pink noise contains the degree of persistency that characterizes healthy repetitive movement [4].

Feedback and target cues were provided as a yellow and a red dot respectively (Fig. 1). The instruction for the SELF condition was *"sway back and forth, in your preferred pace and amplitude, as if you would be doing the task for the whole day, without rising your heels or toes from the ground".* In the PINK condition participants were simply instructed to follow the red dot as accurately as possible, using the yellow dot which illustrated their CoP instantaneous position. The two trials were randomized to avoid any learning or fatigue effect.

2.3. Complex (Pink noise) target generation

The target's motion was constructed to contain persistent amplitude and cycle durations. For this reason, two pink noise time series of 132 data-points were generated using the "pinknoise" function in MATLAB (R2014b). In order to ensure the persistent structure of the pink noise time series, the function was modified to generate signals multiple times, while the signal's scalar index α was computed using Detrended Fluctuation Analysis (DFA), until the signal's fractal exponent α reached a value between 0.99 and 1.01, ensuring the representation of a pink noise signal. This step was repeated two times resulting in two different pink noise signals: the first was used for the construction of the target's cycle duration (A) and the second for the target's cycle amplitude (B). The two pink noise signals were normalized to each individual's voluntary sway duration and amplitude registered in the first experimental session. The resultant target signal was created using a simple sinusoidal function of 132 sinewaves of cycle duration A_i and amplitude B_i from the two pink signals:

$$Target\_Signal = B_i \sin\left(2pi\frac{A_i}{uf}t\right)$$

A_i and B_i represent the ith frequency and amplitude element respectively, of the normalized pink noise vectors, uf is the update frequency of the signal, and t is the time vector.

2.4. Data reduction and analysis

We analyzed the data of the second session. Postural sway cycle durations, amplitudes and velocities were calculated from the CoP time series. The first and last two cycles were excluded, resulting in 128 cycles for each condition. Sway cycle duration was defined as the time interval between two consecutive onsets of sway cycle. The onset of a cycle was defined when CoP crossed the middle of the foot-length while moving anteriorly. Each cycle amplitude was calculated as the difference between the maximum (forward) and minimum (backward) CoP displacement. Velocity was calculated as the mean of instantaneous velocities over the cycle. Regarding our first hypothesis we calculated a) the coefficient of variation (CoV) as a measure of the magnitude of variability and b) the fractal exponent α, calculated with Detrended Fluctuation analysis (DFA), as a measure of temporal structure of variability in terms of persistency, computed for sway cycle durations, amplitudes and velocities. For our second

hypothesis we computed the cross-correlation function (CCF) between the visual target and the postural sway, for both amplitudes and durations.

2.4.1. DFA algorithm

DFA was used to assess the degree of persistency of postural sway parameters (duration, amplitude, velocity), extracting the fractal exponent α for each parameter's time series [22]. The algorithm is described in detail elsewhere [22]. In short, the raw time series of length N is integrated, and separated into boxes of size n. Each box is then detrended and the Root Mean Square (RMS) fluctuation is calculated and averaged across boxes. This process is repeated for each box size. In this analysis, box sizes from 4 data points to N/4 were selected after statistical analysis of the minimum standard deviation between different combinations of box sizes. The exponent α, is the resultant slope of the log-log plot between the box size and the RMS fluctuation for each box selected for the analysis (Fig. 2). Where α < 0.5 indicates an anti-persistent behavior, with fluctuations that are independent and almost constant across the different box sizes. Increasing values (α > 0.5) indicate greater persistency.

2.4.2. Cross-correlation function analysis

The cross-correlation function (CCF) was used to evaluate the degree of amplitude (sway amplitude-target amplitude) and duration (sway duration-target duration) coupling. Practically, the time lag of the peak CCF identifies whether the amplitude and the duration of the current sway cycle couples with the current (synchronization), the previous (reaction), or the next cycle of the visual target (anticipation) [9]. We computed the CCF between the visual target's motion and CoP cycle duration and amplitude from lag-10 to lag+10, while one lag unit refers to one cycle duration or amplitude. All analyses were performed using MATLAB software (MATLAB_R2014b).

2.5. Statistical analysis

All dependent measures were normally distributed (Shapiro-Wilk's test, $p > 0.05$) and did not indicate any violations of the sphericity (Mauchly's test, $p > 0.05$). In order to test our hypothesis, paired samples t-tests were used in order to assess whether the CoV and fractal exponent α of sway cycle and amplitude are different between SELF and

PINK conditions. Significance level was set at p < 0.05. All statistical analyses were performed using SPSS (version 25.0).

3. Results

Representative data for the 128 cycle durations and amplitudes during the SPFB and PINK and the log-log plots between window sizes and RMS fluctuations are presented in Fig. 2. The postural sway frequency ranged from 0.26(±0.05) to 0.41(±0.06) Hz for SELF and from 0.25(±0.04) to 0.44(±0.07) Hz for the PINK condition. The range of postural sway amplitude, normalized to the participants' foot-length(%) was 43.42(±10.86)–69.05(±8.96) for SELF and 44.05(±8.20)–71.64(±5.28) for PINK.

3.1. Magnitude of postural sway variability

Tracking of the visual target (PINK) significantly increased the CoV (Fig. 3, left column) of sway cycle duration ($t_{(19)}$ = 5.909, p < 0.001), amplitude ($t_{(19)}$ = 5.914, p < 0.001) and velocity ($t_{(19)}$ = 12.342, p < 0.001).

3.2. Temporal structure of postural sway variability (persistency)

All sway cycle variables showed persistent behavior (α > 0.5) in both task conditions (Fig. 3, right column). However, the fractal exponent α significantly decreased for sway duration ($t_{(19)}$=-4.533, p < 0. 001) while it increased for sway amplitude ($t_{(19)}$ = 2.686, p = 0.015) when participants tracked the complex motion of the visual target. The persistency of sway velocity remained unchanged between conditions (p > 0.05).

3.3. Sway-target coupling

Fig. 4 shows the CCF coefficients between the target and the CoP sway cycle duration and amplitude plotted for lags ranging from -10 to 10. The maximum CCF coefficient for sway amplitude and duration appeared at different time lags. This was noted at lag+1 for CoP-target sway duration while it was noted at lag0 for amplitude.
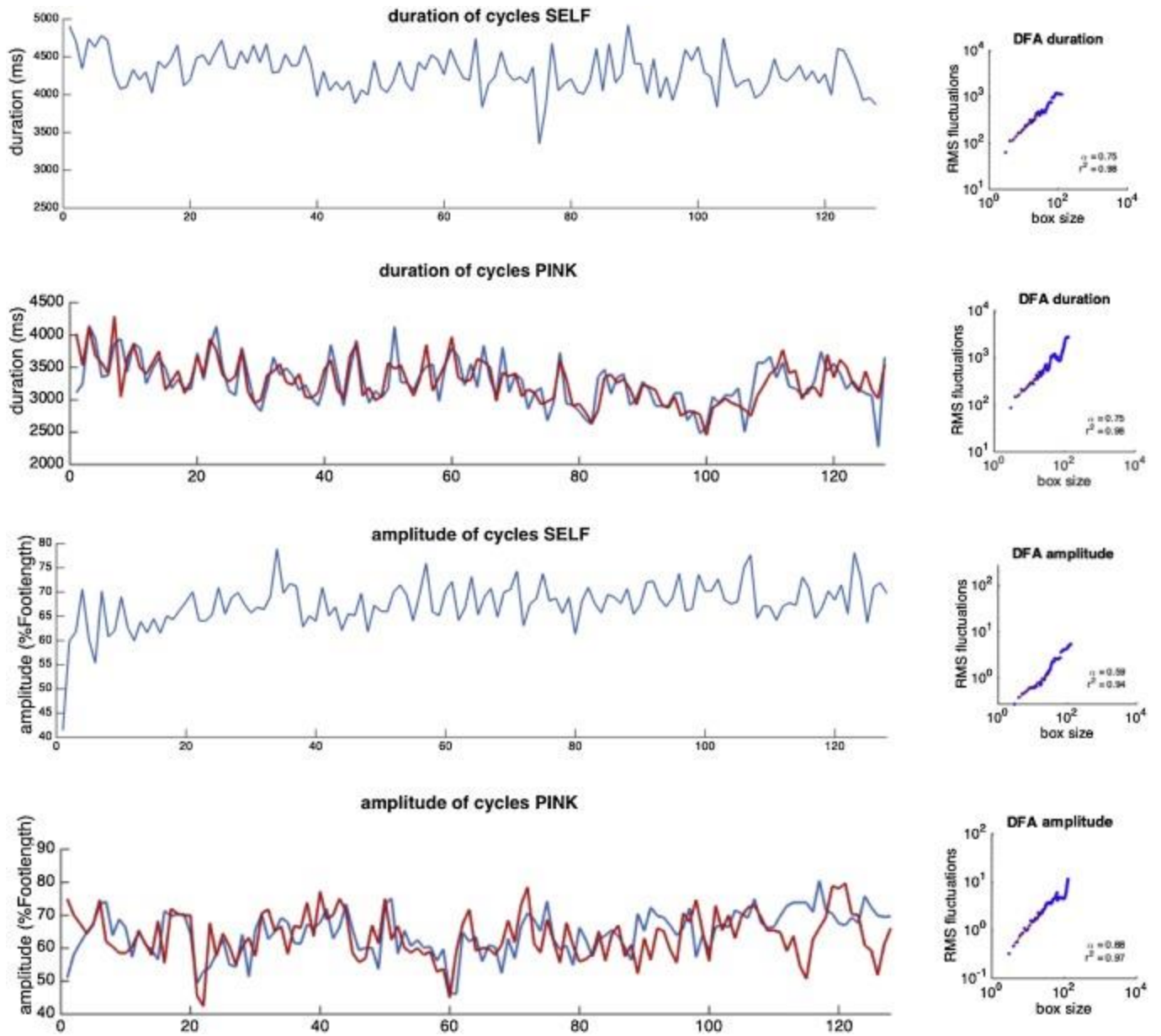
Fig. 2. Left column illustrates the representative data from one participant for the cycle duration (top rows) and amplitude (bottom rows) of SELF and PINK conditions. For the PINK condition the respective target cycle durations and amplitudes are also shown (red lines). The right column illustrates the log-log plot between the box size and the RMS of fluctuations for duration and amplitude in the two conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

The goal of the present study was to investigate whether swaying to the complex motion of visual target can modulate the magnitude (i.e. measures of variance) and temporal structure (i.e. persistency) of voluntary sway variability. Sway cycle variance increased when tracking the visual target. Sway persistency also changed, albeit in different directions, resulting in more persistent amplitude variations across cycles while cycle duration became less persistent. Additional analysis of the coupling between the target and the sway cycles revealed more synchronous spatial than temporal coupling to the target.

4.1. Tracking the complex target motion modulates variance and persistency of sway

When sway was guided by the complex visual target, the variance of sway cycle duration, amplitude and velocity, increased compared to the self-paced sway. Whether this increase benefits sway control is not clear. On the one hand, movement variability has been related to noise in the nervous system [23] and treated as a fingerprint of movement failure [24]. On the other, increased movement variability suggests feedback-based error corrections that are related to exploratory behavior [25]. Our results are in line with the latter view, since the unpredictable nature of the visual target motion necessitated feedback-based corrections using perception-based action [11]. Sway persistency increased for cycle amplitude, decreased for cycle duration and did not change for cycle velocity when tracking the visual target motion. These different modulations can be explained by the nature of the sensory information used to guide postural sway. Although the visual target provided information about both sway cycle duration and amplitude, vision serves the sensorimotor system as the dominant modality for spatial coupling, while it contributes less to temporal synchronization [26]. Discrete auditory or visual rhythms, such as beeps or flashes on the other hand are more appropriate for synchronization in time [26]. Therefore, the spatial information provided by the continuously visible target motion in our paradigm might have improved the persistency of the cycle amplitude at the cost of cycle duration persistency. Furthermore, the spatial error information between the CoP and the visual target that was fed-back to the participant may also lead to a prioritization of spatial over temporal

coupling [27]. It is also possible that the persistency of cycle duration and amplitude are co-modulated in order to preserve the persistency of sway velocity.
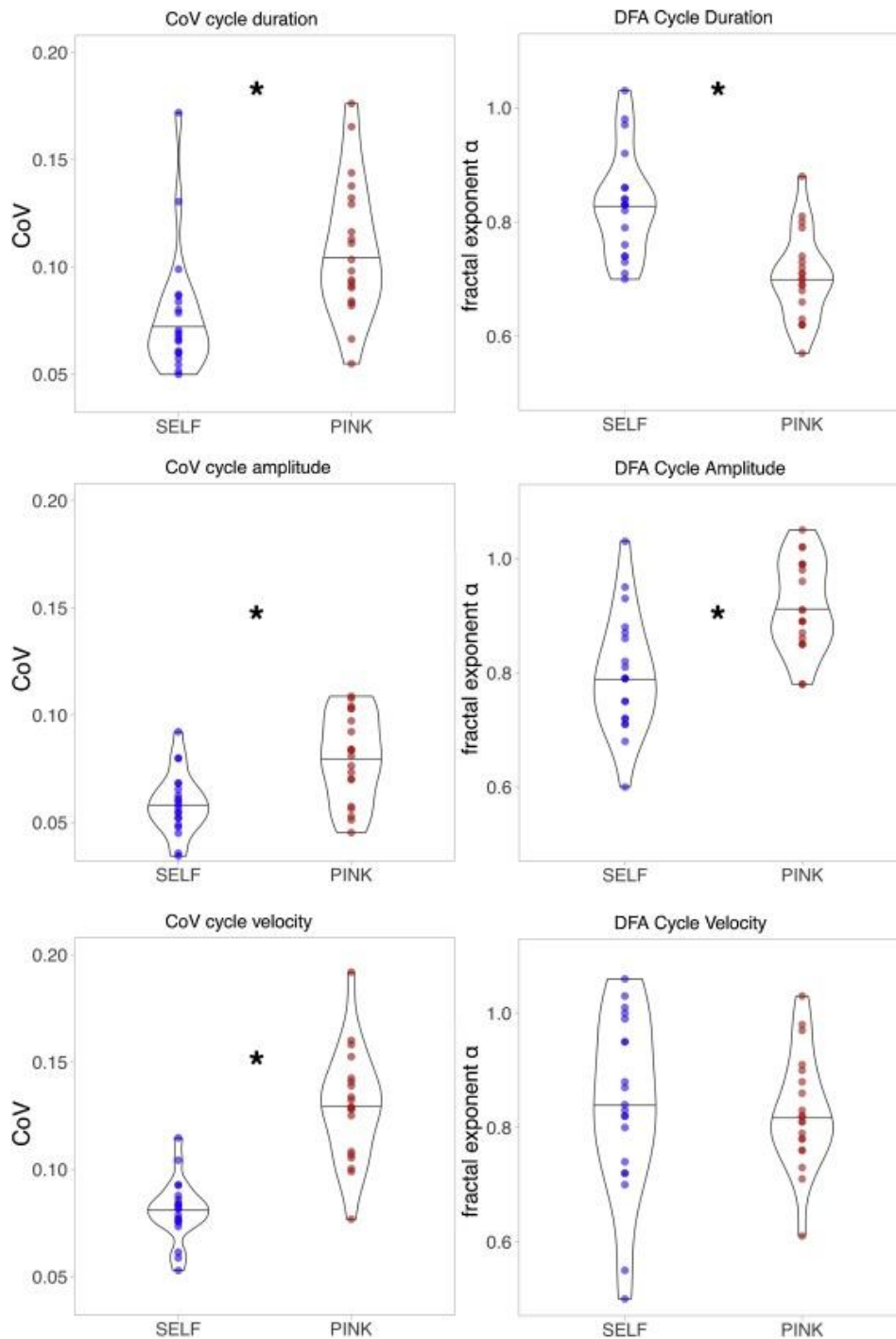

Fig. 3. Violin plots. Individual cases are represented by circles and group-means by dashes for cycle duration (up), amplitude (middle) and velocity (bottom). CoVs are illustrated in the left column and fractal exponent α in the right. Asterisks indicate significance at p < 0.05.

4.2. Spatial and temporal coupling to the target motion occur at different time lags

Cross-correlation analysis between the CoP and the target cycle revealed a consistent peak for both cycle amplitude (0.36) and duration (0.42). Correlation values, although relatively low, are in line with previously reported literature in walking synchronization using variable auditory [28] or visual metronomes [29]. In the current experiment however, the peak correlation was noted at different time lags for sway cycle amplitude and duration. Interestingly, the target-sway cycle duration correlation peaked at lag+1 for most participants. This suggests that participants attempted to correct each cycle duration, based on the duration of the previous target cycle, revealing a unidirectional exchange of information [11] which results in a weaker modulation of movement's persistency [28]. A stronger modulation of persistency requires the bi-directional exchange of information which is the case of information exchange between biological systems, when for example two partners walk side by side while holding hands [30]. In this case, the stronger modulation could be due to the wealth of sensory information (visual, auditory, haptic) exchanged between partners. When participants were asked to walk in synchrony with a complex visual metronome, the persistency of stride durations remained unchanged [29]. Moreover, participants anticipated the target stride duration in contrast to our study revealing a reactive correction to the target cycle duration. This difference may be attributed to the different tasks per se; voluntary sway in the antero-posterior direction while tracking a visual motion cue is a novel task that participants executed for the first time when visiting the lab, while walking is a foremost automatized, every-day performed activity. In addition, the visual target used in the current study imposed both spatial and time variations of the sway cycle. Thus, spatial coupling occurs with the current target cycle in the absence of inter-cycle corrections, which may explain the increase of cycle amplitude persistency.

4.3. Conclusions and Implications for balance rehabilitation

Tracking of a complex visual target motion improves the persistency of sway cycle amplitude at the cost of reducing the persistency of cycle duration. These differential modulations may be explained by the relevance of visual information for the spatial coupling of postural sway to the target motion. Our results suggest that tracking the complex motion of a visual target may be employed as a stimulus to modulate the
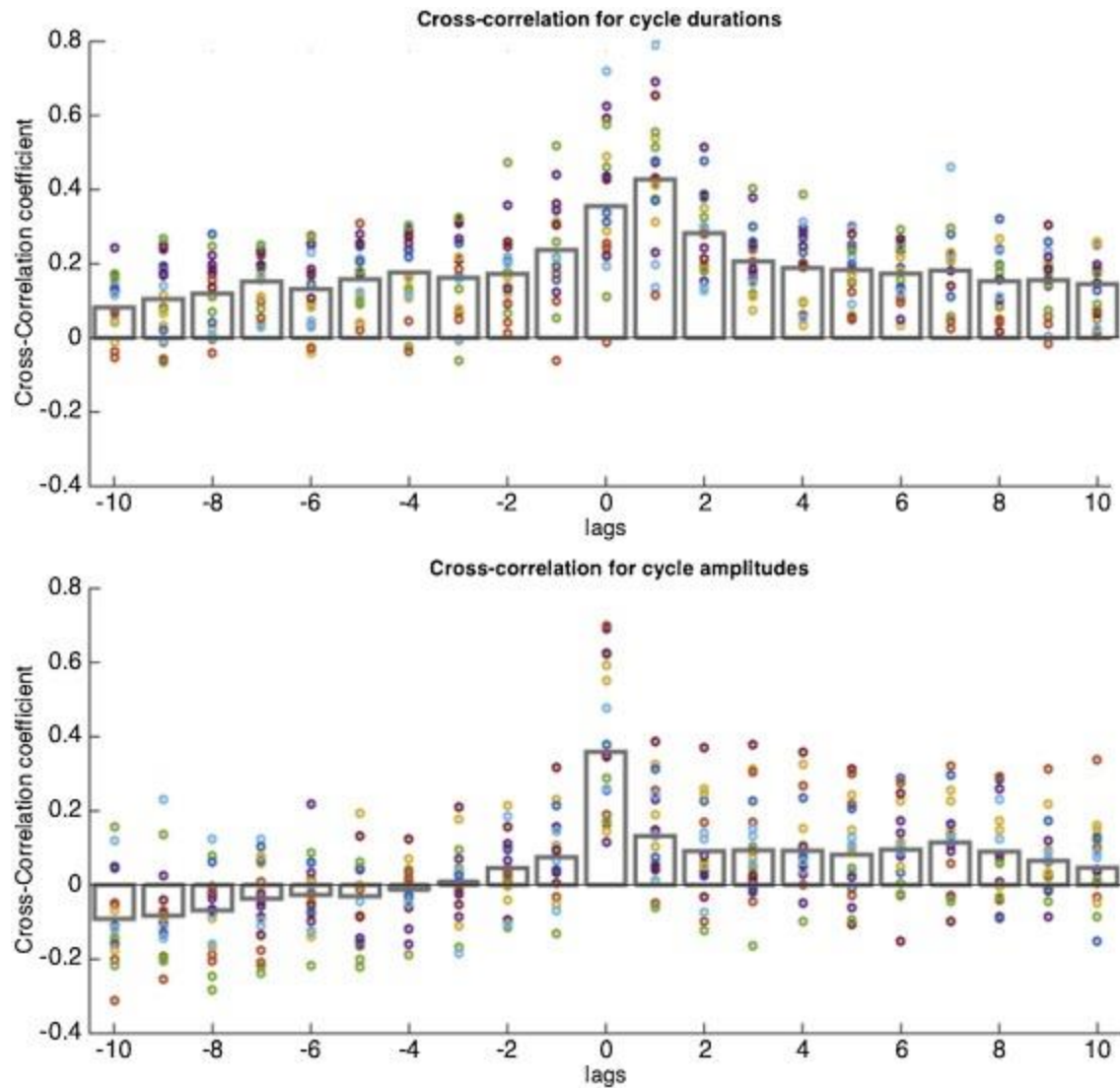
Fig. 4. CCF for the PINK condition between visual target and CoP movement in the AP direction for cycle duration (top) and cycle amplitude (bottom). Colored dots represent individual values. Bars represent the average coefficient at each lag.

spatial dynamics of voluntary postural sway which may be important for the exploration or even enhancement of the stability limits when voluntarily shifting body weight during the execution of daily life tasks. Further research is required in order to explore this possibility in people with balance disorders such as older adults or neurological patients.

Some limitations of the present study also need to be considered. First, analysis of the persistency requires long series of repeated observations. In our analysis we used a length of 128 durations, amplitudes and velocities limiting the overall duration of the task

to 6 min, in order to avoid fatigue or lack of concentration. Second, the target motion was normalized to each participants' initial parameters of self-selected voluntary sway. However, it may render each participant's target motion to reach different minima and maxima, for both amplitude and duration, resulting in an inherently different variability of the target motion between participants. Third, the results of the present study need to be interpreted with caution when investigating the mechanisms of static postural control. Although voluntary shifting body weight is an important element of every-day locomotive activities, our results cannot be generalised to quiet standing, where sway is spontaneous and therefore might be differently controlled.

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