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Standing or swaying to the beat: Discrete auditory rhythms entrain stance and promote postural coordination stability

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ABSTRACT

Humans seem to take social and behavioral advantages of entraining themselves with discrete auditory rhythms (e.g., dancing, communicating). We investigated the benefits of such an entrainment on posture during standing (spontaneous entrainment) and during a whole-body swaying task (intentional synchronization). We first evaluated how body sway was entrained by different auditory metronome frequencies (0.25, 0.5, and 1.0 Hz). We then assessed the stabilizing role of auditory rhythms on postural control, characterized in a dynamical systems perspective by informational anchoring of the head (local stabilization) and fewer transitions from in-phase to anti-phase ankle-hip coordination (global stabilization). Our results revealed in both situations an entrainment of postural movements by external rhythms. This entrainment tended to be more effective when the metronome frequency (0.25 Hz) was close to the dominant sway frequency. Particularly, we found during intentional synchronization that head movements were less variable when paced by a slower beat (informational anchoring), and that phase transitions between the two stable patterns in postural dynamics were delayed. Our findings demonstrate that human bipedal posture can be actively or spontaneously modulated by an external discrete auditory rhythm, which might be exploited for the purpose of learning and rehabilitation.

1. Introduction

Upright bipedal stance is one of the most common postures that humans use to interact with their environment. Information originating from optical, inertial or mechanical stimulation plays a crucial role in the control of balance [1]. To date, a great emphasis has been placed on the role of vision for the regulation of stance [2,3] and posture [4]. Postural responses of human participants to visually-driven environments, in general of sinusoidal nature, have been largely studied using a moving room [2] or a simple virtual environment [5]. Using a head tracking task, Bardy and colleagues [6,7] showed that despite the many body's degrees of freedom, tracking performance relied on two spontaneous stable coordination patterns between the ankles and the hips. Depicted by their phase relation, these two coordination patterns, namely the in-phase pattern (0°–20°) and the anti-phase (160°–180°) pattern, were respectively observed for low and high target frequencies. Phase transition from in-phase to anti-phase ankle–hip coordination occurred when the frequency of the driving visual stimulus reached a critical level (0.5 Hz). Similar results were found in the presence of an audible environment [8,9], in studies where participants were instructed to couple their head movements with the acoustically specified motion of the room. Although participants showed a remarkable facility to couple their postural movements to a continuous acoustic structure, it still remains an open question as to whether discrete auditory rhythms produce the same effect. For instance, a high frequency acoustic field (1000 Hz-tone) often destabilizes postural sway [10,11] whereas a rhythmic acoustic stimulation such as a sound wave or a musical groove with a salient beat often decreases sway variability [12,13]. In the literature, the role played by discrete acoustic information is rarely considered for the regulation of balance, and in general the auditory conditions leading to a stabilizing effect remain unclear. This question is of interest since several human actions involve spontaneous or intentional synchronization with salient auditory beats such as in music and dance. In addition, because discrete auditory rhythms provide a strong reference point, the stability of rhythmic movements is often enhanced when the beat coincides with a salient reference point such as reversal points in the movement cycle, a phenomenon known as the *anchoring effect* [14,15]. While the use of rhythmic auditory stimuli has become very popular to entrain and stabilize various biological movements, their effect on posture remains

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unclear [16–18].

In this study, we examined the coupling effectiveness of discrete auditory rhythms on postural movement, especially for postural regulation. Given the apparent propensity for individuals to have their movements entrained by rhythmic beats [19,20], we tested different coupling strengths such as a spontaneous entrainment when standing (weak coupling) *versus* an intentional posture-beat synchronization during periodic sway (strong coupling). Moreover, in order to modulate postural coordination [6] and adjust the detuning factor (i.e. the frequency difference between two coupled-oscillators before their interaction), we selected different metronome frequencies (0.25; 0.5 and 1.0 Hz). For intentional conditions, we expected that the postural system would be driven by a rhythmical auditory stimulus, and that the stability of postural coordination patterns (in-phase and anti-phase) would be enhanced by the beat. We also expected an informational anchoring, reflecting a local stabilization of audio-postural synchronization. Precisely, we expected that postural movements would be more regular at the reversal point coinciding with the metronome signal. Finally, as the coupling strength is weaker for spontaneous entrainment, we predicted that the entrainment would occur for frequencies that are closer to the participant's preferred frequency [21,22].

2. Method

2.1. Participants

Twenty healthy participants (9 women) aged between 18 and 26 years (20.65 ± 1.72) took part in this experiment. All reported normal vision, normal audition, and no history of vestibular disease that would affect their participation. Their mean height was 1.70 m (*SD* = 9.38) and their mean weight was 63.2 kg (*SD* = 13.19).

2.2. Task and procedure

Participants stood barefoot on a force plate, arms along the body and the gaze directed onto a fixation point (black cross 15 × 15 cm) located in front of them at a 5 m distance. They wore wireless earphones providing the auditory stimuli, remotely controlled by a distant computer. Auditory metronomes were generated using isochronous sequences of discrete beeps with pure tones of 80 ms at a frequency of 880 Hz, via MathWorks Matlab. The earphone volume was adjusted for each participant to be comfortable.

The experiment was conducted in two steps, corresponding to the two experimental conditions (spontaneous and intentional), with three trials per frequency exposure. Firstly, in the spontaneous entrainment condition, participants were exposed during 60 s to a metronome beeping at different frequencies while standing quietly: 0.0 (silence); 0.25; 0.5; and 1.0 Hz. No instruction was given about how to synchronize with the metronome, in order to observe a possible entrainment effect. Secondly, in the intentional synchronization condition, participants were asked to sway rhythmically in the anterior-posterior (AP) direction at a metronome guided pace of 0.25, 0.5, and 1.0 Hz. Specifically, they were instructed to synchronize the maximum forward leaning position of their head to each successive beat in order to maintain a constant 1:1 relation. Participants received no instruction about which postural patterns or which amplitude to adopt.

2.3. Data analysis

Kinematic data was recorded with an AMTI force plate (AMTI, BP400600-2000, 60 × 40 cm, 1000 Hz) and eight infrared cameras (Nexus MX13 Vicon System ©, 100 Hz) tracking five reflective markers placed on participant's right side. Markers were located on the head (forehead), shoulder (acromion), hip (greater trochanter), ankle (lateral malleolus) and toe (head of the first metatarsal) as illustrated in Fig. 1A.

The first and last five seconds were removed from the data analysis to avoid transient behavior. The antero-posterior CoP displacements, as well as the angular displacement of hips and ankles, were detrended and low-pass filtered with a dual-pass second-order Butterworth filter at a cut-off frequency of 10 Hz before the following analysis:

2.3.1. External intentional postural entrainment

In order to evaluate whether participants were able to intentionally synchronize their movements with the metronome, the discrete relative phase was computed and its circular standard deviation [23]. Using the metronome temporal series as a reference, positive values of relative phase indicated that head movements were following the stimulus and negative values indicated that head movements were preceding the stimulus. The circular mean relative phase reports the synchronization accuracy, and the circular standard deviation specifies the stability over time (phase-locking). In other words, ideal performance in this auditory-head synchronization task would produce relative phase and circular standard deviation values near zero.

2.3.2. Informational anchoring

As suggested by previous studies [14,15], auditory-motor synchronization leads to informational anchoring resulting in a decrease of thickness (variability) in the limit cycle. To assess the local stabilizing role of auditory stimulation during volitional entrainment, we reconstructed normalized phase portraits from the position (*x-axis*) and velocity (*y-axis*) of the head time-series. Then, we extracted thickness by computing the standard deviation of the data distribution every 30° into the limit cycle, yielding 12 regions of interest (see Fig. 2).

2.3.3. External spontaneous postural entrainment

Spectral analysis was chosen for detecting frequency-locking patterns characterizing entrainment. Indeed, the discrete nature of the metronome prevents any computation of the continuous relative phase. Similarly, the discrete relative phase [23] isn't applicable since the identification of remarkable events in quiet stance signals such as inflection points or reversals points is extremely difficult. To determine the frequency entrainment of postural sway toward the metronome frequency, we computed the power spectral density (PSD) function of the antero-posterior CoP signal. Then, we extracted and compared the PSD energy peaks in the metronome and silence conditions at the following frequencies: 0.25, 0.5 and 1.0 Hz (see Fig. 1C). A frequency-entrainment pattern was obtained when the postural signal exhibited more energy at the frequency imposed by the metronome than in absence of metronome (silence condition).

We also identified the dominant sway frequency when participants stood quietly (silence condition) at the principal (highest) peak obtained in the PSD function to express the frequency detuning (i.e. the frequency mismatch before the interaction of two oscillating system).

2.3.4. Intrapersonal postural entrainment

To examine the global stabilization role of auditory stimulation on postural coordination, we computed the distribution of ankle-hip relative phase data. The continuous relative phase between the hip and ankle angles was extracted by the Cross-Wavelet Transform (CWT) method, using a Morlet mother function of order 8 [24,25]. Then, we classified the occurrence of the relative phase angles in each of nine 20° relative phase regions ranging from 0° to 180° [22,25].

In addition, head displacement during each intentional trial was expressed in terms of mean amplitude. Mean amplitude was used because movement amplitude was unconstrained and may affect the coordination modes adopted by our participants.

2.4. Statistical analysis

All variables were averaged over the three repetitions in each experimental condition. For the external spontaneous postural entrainment variable, we performed a one-sample *t*-test on the difference in