Motor Control, 2004, 7, 174-187

Task-specific Stabilization of Postural Coordination During Stance on a Beam

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Surfaces shorter in extent than the feet elicit multi-joint coordination that differs from what is elicited by stance on extensive surfaces. This well-known effect arises from the mechanics of the actor-environment interaction. Multi-joint control of stance is also known to be influenced by non-mechanical aspects of a situation, including participants' task or intention. Intentional constraints do not originate in mechanics, and for this reason one might suppose that constraints imposed by mechanics would dominate constraints imposed by intentions, when the two were in conflict. We evaluated this hypothesis by varying participants' supra-postural task during stance on a short surface. While standing on a 10-cm wide beam, participants were exposed to optic flow generated by fore-aft oscillations of a moving room. Participants faced a target attached to the front wall of the moving room and were asked either to look at the target (with no instruction to move) or intentionally to track it with their head (i.e., to keep the target-head distance constant). Within trials, we varied the frequency of room (and target) motion, from 0.15 to 0.75 Hz, in steps of 0.05 Hz. In both conditions, ankle and hip rotations exhibited anti-phase coordination, but behavior was not identical across conditions. Coupling between motion of the room and the head was stronger for the tracking task than for the looking task, and the stability of ankle-hip coordination was greater during tracking than during looking. These results indicate that the influence of support surface mechanics did not eliminate the influence of the supra-postural task. Environment-based and task-based constraints interacted in determining the coordination of hips and ankles during stance.

Key Words: posture, intention, constraints, emergence, sway, moving room

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Introduction

There are several situations in which people stand or move on a narrow surface of support. Examples include gymnasts who execute complex movements on a beam and people riding skateboards. To understand why the body is coordinated in a certain way in such situations, it is necessary to understand the role played by constraints applied to the postural system.

Self-organization of Postural Coordination

Recent research has supported the hypothesis that coordination of ankle and hip rotations in the control of stance can be understood from a dynamical systems perspective. (See Bardy, 2004, for a review.) Studies on self-organization of human behavior including coordination with an external event (e.g., Engström, Kelso, & Holroyd, 1996; Kelso, DelColle, & Schöner, 1990), inter- and intra-limb coordination (e.g., Kelso, 1984; Kelso & Jeka, 1992; Schöner & Kelso, 1988), and inter-personal coordination (e.g., Oullier, de Guzman, Jantzen, & Kelso, 2003; Schmidt, Carello, & Turvey, 1990; Temprado, Swinnen, Carson, Tourment, & Laurent, 2003) have demonstrated that the dynamics of a given system can be captured in one collective variable: the relative phase between two (or more) of its components. Bardy, Marin, Stoffregen, and Bootsma (1999) showed that the postural system is no exception. The relative phase, ϕ_{rel}, between rotations of the ankles and hips ($\phi_{rel} = \phi_{ankle} - \phi_{hip}$) is a collective variable that can serve as an order parameter (i.e., an appropriate low dimensional global descriptor; see Kelso, 1995) of the dynamics of postural coordination. Consistently, two stable modes of ankle-hip coordination have been observed: an *in-phase* mode ($\phi_{rel} \approx 20°$) and an *anti-phase* mode ($\phi_{rel} \approx 180°$; Bardy et al., 1999; Marin, Bardy, Baumberger, Flückiger, & Stoffregen, 1999a). Moreover, under the influence of a continuous change of a non-specific control parameter—oscillation frequency—the coordination between ankle and hip joints has been found to exhibit several hallmarks of self-organization (Kelso, 1995), including multi-stability, critical fluctuations, phase transition, hysteresis, and critical slowing down (Bardy, Oullier, Bootsma, & Stoffregen, 2002).

The Role of Constraints on Shaping the Dynamics of Postural Coordination

The high order of complexity defining the postural system and the constant constraints that are applied on it, such as ground reaction and gravito-inertial forces, generate a high level of variability at different levels of observation (Oullier, Marin, Bootsma, Stoffregen, & Bardy, 2004). Stability is determined by interactions among constraints that fall into three classes: those arising from properties of the environment, from the body, and from the goal of the task (Newell, 1986). The effects of these constraints have been studied in the context of human postural coordination.

Environmental Constraints. Studies using moving rooms oscillating in the anterior-posterior axis have reported a strong influence of the room motion on postural oscillations (Lee & Aronson, 1974; Lee & Lishman, 1975; Stoffregen, 1985). Computer-generated optical simulations of moving environments have also been used, and again optical information was found to influence postural oscillations (Dijkstra, Gielen, & Melis, 1992; Dijkstra, Schöner, & Gielen, 1994). Other studies have addressed multi-joint coordination in stance by manipulating the nature of the surface of support (e.g., Crotts, Thompson, Nahom, Ryan, & Newton, 1996; Marin et al., 1999a; Riemann, Myers, & Lephart, 2003; Stoffregen, Adolph, Thelen, Gorday, & Sheng, 1997) or support surface movement (Buchanan & Horak, 1999, 2001; Horak & Nashner, 1986; Jung, Ringenbach, & Lantero, 2003; Mégrot, Bardy, & Dietrich, 2002). Such studies document a strong effect of support surface properties on postural coordination. For example, Bardy et al. (1999) observed that when standing on firm ground, participants adopted the in-phase mode for low amplitude oscillations and the anti-phase mode for high amplitude oscillations. However, Marin et al. (1999a) showed that when standing on foam, regardless of the amplitude of oscillations, the anti-phase mode was adopted. The same effect was found when untrained subjects where standing on a narrow surface of support (Marin, Bardy, & Bootsma, 1999b).

Body Constraints. Properties of the body are known to influence postural coordination. For instance, body stiffness is modulated by sport expertise and training (Marin et al., 1999b; Perrot, Deviterne, & Perrin, 1998; Vuillerme, Danion, Marin, Boyadjian, Prieur, Weise, & Nougier, 2001). Such factors can change the dynamics of the postural system. For instance, gymnasts can maintain in-phase coordination of the hips and ankles in situations in which non-gymnasts resort to anti-phase coordination (Marin et al., 1999b). Body properties have also been manipulated experimentally in order to assess their role on postural coordination. Bardy et al. (1999) tested the effects of artificial variations of foot length and height of the center of mass on hip-ankle coordination in stance. They found that lowering the center of mass or lengthening the feet tended to favor in-phase coordination of the hips and ankles, while raising the center of mass or shortening the feet tended to favor anti-phase coordination.

Task Constraints. Finally, characteristics of body sway are also known to be influenced by the tasks in which standing participants engage. The goal of tasks such as quiet stance (e.g., Aramaki, Nozaki, Masani, Sato, Nakazawa, & Yano, 2001) or maintaining a certain posture in classical ballet (e.g., Hugel, Cadopi, Kohler, & Perrin, 1999) is to achieve a given postural state. But postural sway also is influenced by tasks that have no direct relation to stance. For example, oscillations of the body can be modulated adaptively to support visual search tasks (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000) to maintain stable fixation on targets at different distances (Stoffregen, Smart, Bardy, & Pagulayan, 1999b), during performance of spatial memory tasks (Kerr, Condon, & McDonald, 1985), verbal reaction time tasks (Hunter & Hoffman, 2001), Stroop tasks (Dault, Frank, & Allard, 2001), and tasks requiring eye movements (e.g., White, Post, & Leibowitz, 1980). Tasks such as these that are super-ordinate to the maintenance of posture are called supra-postural tasks (Stoffregen et al., 1997).

In spite of the variety of studies in the literature (see Woollacott & Shumway-Cook, 2002, for a review), to our knowledge only one study has addressed the influence of supra-postural tasks on postural coordination. Oullier, Bardy, Stoffregen, and Bootsma (2002) examined the influence of task (of intention) on ankle-hip coordination in stance. Participants were standing in a moving room, facing a target attached to the front wall. The room was moving back and forth in the anterior-posterior axis with a constant amplitude, while its frequency was increased or decreased. In the tracking task, similar to the one used by Bardy et al. (1999, 2002), participants were asked to use head movements to track the target oscillations by keeping a constant distance between the target and their head. In a second task, they only had to look at the moving target with no head movement imposed by the task, unlike tracking. For both tasks, fore-aft oscillations of the target favored the in-phase mode at low frequencies while, at high frequencies, they favored the anti-phase mode, in line with previous results (Bardy et al., 2002). Stability of each coordination mode was measured by the variability of the ankle-hip relative phase. The task manipulation (tracking vs. looking) had a significant effect on the stability of the coordination modes. During the looking task, both the in-phase and anti-phase modes were significantly less stable than during tracking (Oullier et al., 2002). This result confirmed that postural coordination can also be constrained by properties of the supra-postural task (looking at or tracking a target), as the intention to track had a stabilizing effect.

Interaction of Constraints

In summary, the separate effect of the constraints reviewed in the previous section are well known. What remains uncertain is whether their interaction can influence postural coordination. Previous research has shown that, separately, environmental and bodily constraints can provoke qualitative changes in the dynamics of the postural system. For instance, increasing the oscillating frequency provokes a phase transition from in-phase to anti-phase (Bardy et al., 2002), and the mechanical constraints imposed by standing on a beam favor the anti-phase mode of coordination (Marin et al., 1999b). As far as task intention was concerned, no qualitative change (switch from one coordination mode to another) was observed; only the variability of the ankle-hip relative phase changed. During stance on a rigid, extensive floor, tracking a target instead of simply looking at it decreases the variability of the coordination without triggering any phase transition (Oullier et al., 2002).

In the present study, intentional constraints (a looking task vs. a tracking task) and the frequency of target oscillation were co-varied during stance on a narrow beam. Our goal was to assess the effect of the interaction of these three constraints on the emergence of postural patterns. We sought to determine whether the previously reported effects of supra-postural task and/or frequency of oscillation on hip-ankle coordination would be preserved in the face of the substantial mechanical changes brought about by stance on a balance beam.

Materials and Methods

Participants

Twenty-eight University of Cincinnati undergraduate students received course credit for their participation. They were divided randomly into two groups of 14 participants. The experimental protocol was approved by the University of Cincinnati IRB.

Apparatus

Participants stood in a moving room (e.g., Lee & Lishman, 1975; Stoffregen, 1985)—a 240-cm cube, consisting of four walls and a ceiling mounted on wheels running along rails (Figure 1A). The interior of the room was furnished with marble pattern contact paper, providing a readily detectable, naturalistic optical texture. The room was moved by an electric motor under computer control. Movement of the room produced purely optical stimulation, as participants stood on a wooden beam (10 cm wide × 10 cm high × 120 cm long) placed directly on the concrete floor of the laboratory, 1.5 m from the front wall of the moving room (Figure 1). The longer axis of the beam was oriented parallel to the front wall of the moving room. A target (55 cm × 55 cm black square) was attached to the front wall at eye level.

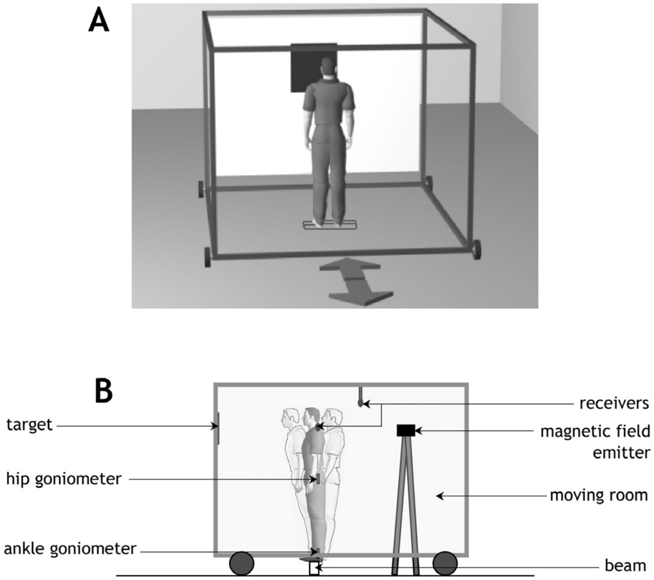

Figure 1 — A. 3-D representation of the moving room. B. The experimental setup, not drawn to scale.

Anterior-posterior motions of the head and the room were recorded using a magnetic motion tracking system (Flock of Birds; Ascension, Inc.). Only linear motion in the anterior-posterior direction was retained for data analysis. A magnetic emitter was fixed at the top of a stand (1.65 m high). A low-intensity magnetic field was created in which the receivers moved, thus allowing for their tracking (Figure 1B). One receiver was attached to the back of the head of the participant and another on the room. During data collection, the stand was placed within the room behind the participant so that the two receivers remained within 50 cm of the emitter, in the area where the greatest amount of spatial resolution was achieved for a measurement accuracy of 1.8 mm. Angular kinematics of the ankle and hip were measured with two electro-goniometers (with a 1° accuracy in measuring fore-aft oscillations) recorded via a Biopac MP-100 system (Figure 1B). One goniometer was attached to the lateral side of the left hip (from the greater trochanter to the iliac crest), and the other was fixed on the anterior side of the left ankle (from the scaphoid to the inferior third of the tibia). A signal sent by the computer controlling the motion of the room triggered data collection at the onset of room oscillations. Data collected by both the Flock of Birds and the goniometers were sampled at 50 Hz.

Procedure

Participants stood barefooted on the beam with their feet parallel, facing the front wall of the moving room (so that the room oscillated along their line of sight), with their arms folded across their chest. They were asked to match the distance between their feet to the distance between their shoulders. Movements of the knees and neck were restricted by the use of adhesive tape that minimized their natural movements in a 2° range (see Bardy et al., 2002). Each group of participants performed a different task. Participants in the looking group were instructed to stay on the beam and to look at the target, with no instruction being given with respect to their head movement. Participants in the tracking group were instructed to stay on the beam and to move their head back and forth so as to maintain a constant distance between their head and the target as the room moved. In both the looking and the tracking tasks, the room oscillated along the anterior-posterior axis with a constant peak-to-peak amplitude of 4 cm. The Up condition contained 13 frequency plateaus lasting 10 cycles each, ranging from 0.15 to 0.75 Hz, increasing in steps of 0.05 Hz. In the Down condition, the frequency of room movement began at 0.75 Hz and decreased to 0.15 Hz in the same fashion. This (ramping) Up versus Down design was used to control for possible order effects (see Bardy et al., 2002). The experimental design was therefore 2 Tasks (looking and tracking) × 2 Conditions (Up and Down). Each trial lasted about 8 min and was performed once by each participant. Participants were given a 5-min break between trials. Trials in which participants fell from the beam were terminated and repeated. Ten trials were repeated in the looking experiment and three in the tracking one. Trial order was counterbalanced across participants.

Variables and Data Processing

Data were band-pass filtered (0.05–5 Hz) prior to analysis. Dependent variables included (a) the cross-correlation R between the head and the target as an index of the strength of the coupling between the participant and the stimulus. Linear statistics were performed on Z values—that is, the Fisher-transformed values of *R;* (b) the peak-to-peak ankle-hip relative phase ϕ_{rel} that summarizes the postural coordination adopted by the participants (Zanone & Kelso, 1997)[1]; (c) the mean angular deviation of ϕ_{rel}, SDϕ_{rel} per frequency plateau, which served as an indicator of the stability of the coordination modes. Circular statistics methods were used on ϕ_{rel} and SDϕ_{rel} (Batschelet, 1981). For all variables, data from the Up and the Down condition were collapsed by frequency plateau in order to counter possible hysteresis effects (see Oullier et al., 2002).

Results

Visual Coupling

A two-way ANOVA was performed on the mean values of *R* at each frequency plateau. The results revealed a significant main effect of Task ($F_{1, 24} = 236.42$, $p < .001$), accounting for 39.3% of the total variance, indicating that target-head coupling was stronger for the tracking task ($M = 0.59$, $SD = 0.12$) than for the looking task ($M = 0.23$, $SD = 0.37$). A significant main effect was also found for Frequency ($F_{12, 288} = 2.84$, $p < .001$, 5.8% of the total variance), indicating that *R* decreased when room frequency increased (Figure 2). The Task × Frequency interaction was not significant; hence, tracking the target enhanced the intensity of the coupling between the head and the stimulus, as compared to looking. These results replicate previous reports of a decrease in coupling with increases in frequency (Oullier et al., 2002) and similar phenomena observed when amplitude was increased (Dijkstra et al., 1992).

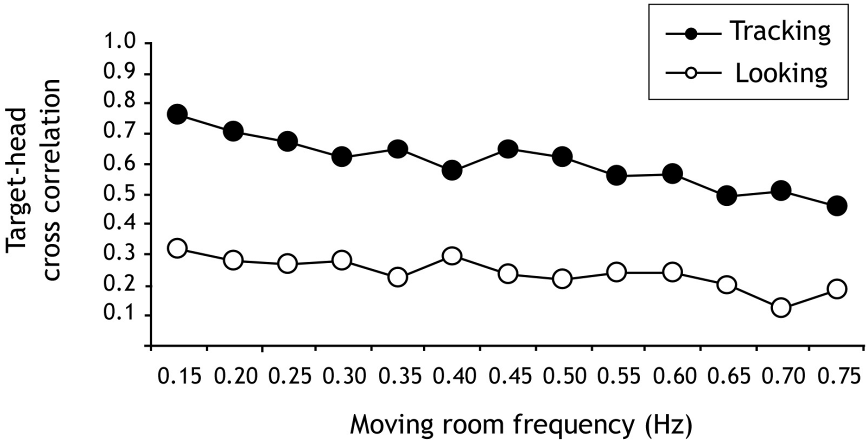

Figure 2 — Mean target-head cross correlation for each frequency plateau, in each task.

Ankle-Hip Coordination

Before performing statistics on ϕ_{rel}, the values were pooled in order to examine the nature of their distribution. As shown on Figure 3, the distribution was uni-modal for both tasks (tracking and looking). A Watson-Williams test, performed in order to compare the values of the angular mean of ϕ_{rel} for each plateau, exhibited no significant effect of the task ($F_{\text{Watson-Williams, 1, 24}} = 2.73$, not significant).

Observation of Figure 3 reveals that the values appear to be centered around 180°. Such observation is confirmed by the grand mean of ϕ_{rel} across frequency plateaus in each task resulting in 185.1° (*SD* = 9.56) when looking (Figure 3A) and 179.3° (*SD* = 7.11) when tracking (Figure 3B). For both tasks, the relative phase values were clustered around a mean (significant Raleigh test for non-homogeneity,

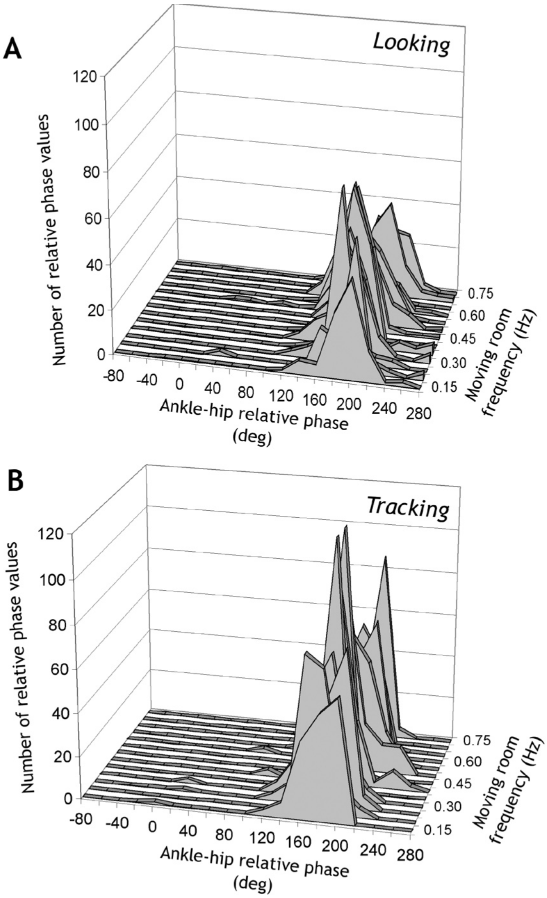

Figure 3 — Distribution of ankle-hip relative phase values (in 20° frequency bins) as a function of room motion frequency for looking (A) and tracking (B).

$p < .05$), indicating a preferred phase angle around 180°. This value ($\phi_{rel} = 180°$) was included in the 95% confidence interval when looking ($179.1° < \phi_{rel} < 190.9°$) and tracking ($174.9° < \phi_{rel} < 183.6°$). Because of the effect of frequency on the coordination mode adopted (see Bardy et al., 1999, 2002), the values of ϕ_{rel} were compared in both tasks for low frequencies (0.15 to 0.40 Hz) and high frequencies (0.45 to 0.75 Hz). Comparisons revealed no significant difference between high and low frequencies for neither looking ($F_{\text{Watson-Williams}, 1, 1420} = 43.32$, not significant) nor tracking ($F_{\text{Watson-Williams}, 1, 1473} = 5.64$, not significant).

We also tested the effect of looking versus tracking on the standard deviation values of ϕ_{rel} for each frequency plateau and found a considerable effect of the task ($F_{\text{Watson-Williams}, 1, 24} = 57.41$, $p < .001$; Figure 4).

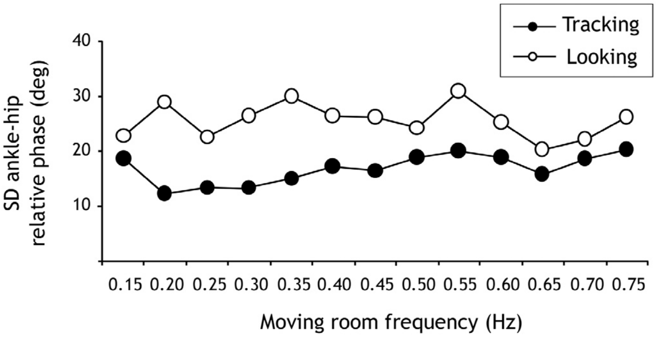

Figure 4 — Average circular deviation of ϕ_{rel}, for each frequency plateau, in each task.

Overall, the ankle-hip coordination results suggest that the anti-phase pattern, adopted in the execution of both tasks, was more variable when looking than when tracking (see Figures 3 & 4). This result suggests that coordination is more stable when tracking the target. The stabilizing effect of tracking is confirmed by the difference between the number of falls in each task (10 in the looking group against 3 in the tracking group).

Discussion

We co-varied two different constraints in order to assess their effects on postural coordination during stance on a narrow beam. The beam provides a strong mechanical constraint that forces the postural system to adopt an anti-phase mode of coordination between the ankles and hips regardless of the frequency of oscillations. The frequency dependence of ankle-hip coordination emergence that is observed on many other situations (i.e., the in-phase mode being adopted at low frequencies of oscillation and the anti-phase mode being adopted for high frequencies, see Bardy et al., 2002) is not observed during stance on a beam. In spite of this strong mechanical effect, we replicated the influence of supra-postural task constraints on hip-ankle coordination that was found by Oullier et al. (2002). That is to say, intention to track the target stabilized postural coordination, as indicated by the lower values of the ankle-hip relative phase angular deviation.

Influence of Motion Frequency and Support Surface

An interesting feature of these results is that the target-head cross-correlation values in the tracking task were lower than those found by Marin et al. (1999b). In Marin et al.'s experiment, participants tracked the target at a constant frequency for 120 s, as opposed to the variable frequency used here (with correspondingly brief frequency plateaus). In the study of Marin et al., participants may have had time to adapt. The higher *R* values obtained by Marin et al. (1999b) are consistent with known long term adaptations of the postural system (e.g., Delorme, Frigon, & Lagace, 1989; Duarte & Zatsiorsky, 2002) that this design did not allow.

We replicated the common finding that the mechanical constraint imposed by standing on a narrow surface has a strong effect on postural control (Aruin, Forrest, & Latash, 1998; Randall, Matthews, & Stiles, 1997; Shupert, Horak, & Black, 1994) . In the present experiment, stance on the beam led to adoption of an anti-phase mode of postural coordination in both the looking (cf. Horak & Nashner, 1986) and tracking tasks (cf. Marin et al., 1999b). On surfaces longer than the feet, an influence of visual motion has been found repeatedly, with low frequencies of visual motion evoking in-phase patterns of postural coordination in both looking and tracking tasks and high frequencies of visual motion evoking anti-phase patterns of postural coordination in tracking tasks (Bardy et al., 2002; Marin et al., 1999a; Oullier et al., 2002) and both in-phase and anti-phase patterns in looking tasks (Oullier et al., 2002). Standing on a 10-cm wide beam, participants in this experiment consistently adopted the anti-phase mode of postural coordination, for the entire range of frequencies tested. One may therefore conclude that the mechanical constraints imposed by the surface of support had a stronger effect on postural coordination than did the constraints imposed by the frequency of room oscillation.

Influence of Supra-postural Task Variation

The beam exercised a powerful influence on coordination but, despite this mechanically based effect, coupling of head motion with room motion was strongly modulated by the manipulation in supra-postural task instructions. During the tracking task, coupling was stronger and more stable than during the looking task. The persistence of supra-postural task effects despite the constraining influence of the beam is the most important result of this study. This finding is consistent with related findings from previous studies in which non-material constraints (instructions or tasks) have been placed in conflict with material constraints (e.g., mechanics of the body or of the support surface; Bardy et al., 1999; Marin et al., 1999a, 1999b; Oullier et al., 2002; Stoffregen, Gorday, Sheng, & Flynn, 1999a). Oullier et al. argued that postural coordination can serve to facilitate performance of supra-postural tasks. They showed that the intention to track a target plays an important role on stabilizing postural coordination modes when participants are performing these tasks on the ground. These results are in line with these findings; the anti-phase mode adopted when tracking the target on the beam was more stable than the one in the looking task. As to the role played by each constraint (frequency, surface of support and intention) on the postural system, it seems that in spite of a strong mechanical effect of standing on a beam, the effect of task (or intention) remains. Therefore, the present results indicate a coexistence between the environmental (beam) and task (looking vs. tracking) constraints rather than one constraint being overwhelmed by the other.

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Note

[1] In several studies, researchers have found it difficult to identify cycles in postural tasks similar to our looking task (e.g., Dijkstra et al., 1994a; Oullier et al., 2002; Stoffregen, 1985). To address this problem, we decided to retain the angular mean value of the relative phase for a given frequency of target oscillation (i.e., a frequency plateau) only if there was a minimum of four unambiguously identified values (out of 10 target cycles per plateau), a method already used in Oullier et al. (2002). If not, the frequency plateau was excluded from the analysis. Only two plateaus were excluded (both in a looking task). Overall more cycles were identified in the tracking conditions, which explains why there are more ankle-hip relative phase values plotted on Figure 3B compared to Figure 3A.

Acknowledgments

The research reported in this article was supported by the National Science Foundation (INT-9603315 and BCS-0236627), and by the French Ministère de l'Education Nationale, de la Recherche et de la Technologie (CNRS/NSF-3899). The authors would like to thank Nat Hemasilpin, Greg K. Nelson, Si Mei, and Dr. Randy J. Pagulayan for their help in running the experiment; Dr. Thierry Ferrand for his help on Figure 1; Drs. Gonzalo de Guzman, Julien Lagarde, and Ludovic Marin for helpful comments on this manuscript; and Dr. J.A. Scott Kelso for critical discussions and support.