7. STABILIZATION OF OLD AND NEW POSTURAL PATTERNS IN STANDING HUMANS

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Abstract

In human stance, rotations around the hips and ankles typically exhibit a relative phase close to 20°, or close to 180°. In this article, we propose a model of stance that captures these postural states and the changes between them. We also describe the results of a recent study in which participants learned a novel pattern of hip and ankle coordination (a relative phase of 135°). Participants learned this novel pattern rapidly. At the same time, learning led to a robust destabilization of pre-existing patterns of hip-ankle coordination. The rate and type of destabilization depended upon the initial stability of the pre-existing patterns. We discuss similarities and differences between the learning of postural and bimanual coordination modes.

Stabilization of Old and New Postural Patterns in Standing Humans

The maintenance of stable upright stance is required in many daily activities in humans and other bipeds. Stable stance requires the body's center of mass to be kept above the feet. Postural control actions consist mainly of coordinated rotations around the hips and ankles. Many patterns of ankle-hip coordination will maintain the center of mass above the feet, but only a few of these are effective across a broad range of situations. Functionality depends in part on the task in which the person is engaged. For example, some coordination patterns that prevent falling may be avoided because they hamper the realization of other, simultaneous goals, such as maintaining gaze, or manual contact with an object. Other coordination patterns may both prevent falling and facilitate performance on these *supra-postural* tasks, and so may be preferred (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999; Stoffregen, Smart, Bardy, & Pagulayan, 1999). This fact has implications for pre-existing patterns of postural coordination, but also for the acquisition of new patterns. In the present contribution, we use existing data on postural transitions to develop a simple model of postural states and postural changes that allow the realization of supra-postural activities. We then examine the problem of learning new postural coordination patterns within the framework of non-linear dynamics of perception and action.

POSTURAL PERSISTENCE AND POSTURAL CHANGE

In our research on postural dynamics (e.g., Bardy et al., 1999; Bardy et al., 2002; Marin et al., 1999; Oullier et al., 2002, 2004), standing participants have been instructed to maintain a constant distance between their head and a visual target that oscillates along the line of sight. They have not been given any instructions about how standing posture was to be controlled during the tracking task. We measured rotations at the ankles and hips, and analyzed the relative phase, $\phi_{\underline{rel}}$, of rotations at these joints. Two coordination modes between ankles and hips have been consistently observed. An *in-phase* mode, with $\phi_{\underline{rel}}$ of about 20–25°, emerged when the visual tracking target moved at small amplitude (e.g., Bardy et al., 1999) or low frequency (e.g., Bardy et al., 2002). An *anti-phase* mode, with $\phi_{\underline{rel}}$ close to 180°, has emerged when the visual target moved with large amplitude or high frequency. The departure from pure in-phase motion ($\phi_{rel} = 0°$) found for low amplitude and frequency contrasts with studies of bimanual coordination (e.g., Haken, Kelso, & Bunz, 1985; Kelso, 1984) and may be a consequence of the frequency competition, $\Delta\omega$, between the upper and lower parts of the body (e.g., Sternad, Amazeen, & Turvey, 1996). It might also result from the mechanical constraint of maintaining the center of mass above the base of support. The differential emergence of these modes was influenced by intentional constraints (i.e., the instruction to track target motion), by behavioral constraints (i.e., height of the center of mass, length of the feet, body stiffness, expertise in sport), and by environmental constraints (i.e., surface properties, target amplitude or frequency); (see Bardy, 2004 for a review). It was the simultaneous, interacting pressures—cooperative or competitive—imposed by the task, the body, and the environment that determined the selective emergence of the in-phase and anti-phase modes (cf. Newell, 1986).

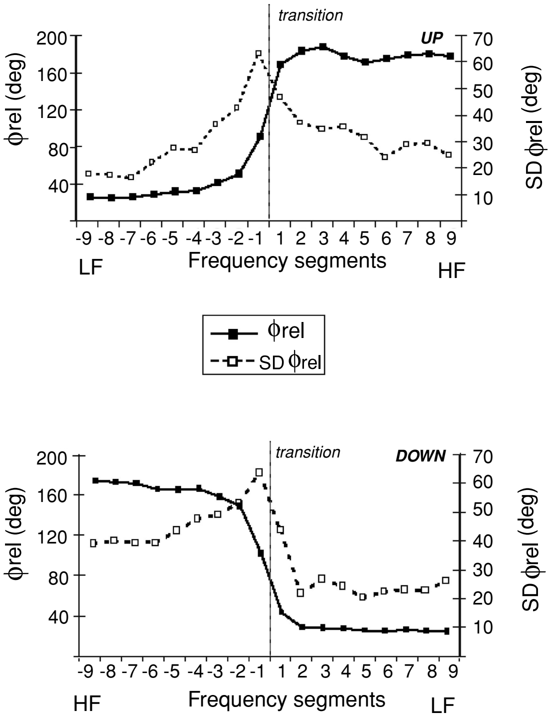


FIGURE 1. Postural transitions in a visual tracking task: Mean point estimate ankle-hip relative phase $\phi_{\underline{rel}}$ (and *SD*) in *Up* and *Down* conditions (10 participants). Each segment includes a temporal average of $\phi_{\underline{rel}}$ over 4 cycles of oscillation, with an overlap of two cycles. *LF* and *HF* refer to low frequency and high frequency segments respectively. Adapted from Bardy et al. (2002). The dynamics of human postural transitions. *Journal of Experimental Psychology: Human Perception and Performance*, 28, 499–514. **PERMISSION REQUIRED**.

We also observed that transitions between in-phase and anti-phase ankle-hip modes revealed characteristics of *non-equilibrium phase transitions* (Bardy et al., 2002). As we increased or decreased the frequency at which the visual target moved, a frequency-induced loss of stability occurred, yielding *critical fluctuations* in the vicinity of the region of the frequency range in which there was a transition between coordination patterns (see Figure 1). Transitions between in-phase and anti-phase modes were abrupt, and exhibited *hysteresis*: Transitions from in-phase to anti-phase occurred at a higher frequency of target motion than transitions from anti-phase to in-phase. Finally, we applied an external perturbation (a sudden shift in the direction in which the target was moving). The perturbation was applied either near to or far from the region (frequencies) in which transitions between modes were known to occur. Each mode was found to be less stable when the perturbation was applied close to the transition region, and more stable when it was applied far from it, as evidenced by a larger relaxation time in the latter situation (*critical slowing down*). In summary, our research has shown that postural modes (i) emerge out of the coalescence of multiple constraints, (ii) exhibit persistence and change that are characteristic of self-organized systems, and (iii) are modulated by the actor's intentions. In the next two sections, we review evidence that (iv) the postural behavior can be modeled using simple tools from biomechanics, and that (v) the learning of new postural modes is accompanied by destabilization of pre-existing dynamics of the postural system.

A SIMPLE MECHANICAL MODEL OF POSTURAL PERSISTENCE AND POSTURAL CHANGE

Research on posture has been a fertile ground for the development of structural or phenomenological models. In pioneering work, Nashner (1976; Nashner & McCollum, 1985), proposed that postural coordination in the maintenance of stance is rooted in the organization of the neuromuscular system. Since then, a variety of mechanical or neurophysiological, structure-related models of the postural system have been proposed (e.g., Barin, 1989; Kuo, 1995; Stockwell, Koozekanani & Barin 1981; Yang, Winter & Wells, 1990). In a different meta-theoretical context, recent developments in the non-linear dynamics of perception and action have inspired the emergence of phenomenological, structure-free models accounting for the self-organization of posture and gait. These latter models use mathematical tools borrowed from non-equilibrium statistical mechanics and stochastic dynamics (e.g., Balasubramaniam, Riley & Turvey, 2000; Dikjstra, Schöner & Gielen, 1994; Kay & Warren, 2001; Schöner, 1991). Attempts to mix the structure-related and structure free models are rare, but do exist. For instance, Taga (1994, 1995) proposed a multi-level model of human locomotion in which the coordination dynamics observable at the behavioral level (i.e., the gait) are consequences of interactions between the neural system and the musculo-skeletal system. Here we propose a simple, mixed model of human posture that captures the behavior of the postural system that has been observed in the tracking task described earlier. Our model is biologically plausible, and is composite in the sense that it is a mechanical model that links joints and segments, with units of mass and length.

The Model. Our preliminary model is a simple, two-segment inverted pendulum system representing the human body. The upper segment represents the head-arms-trunk system and the lower segment represents the legs (*cf.* Figure 2). The segment masses are concentrated and localized at their centers of gravity, and are noted by m_1, m_2 for the trunk and legs, respectively. The segment lengths are noted by l_1, l_2 for trunk and legs, respectively. Muscular and articular damping and stiffness terms are present only at the level of the joints (ankle, hip). The motor command is modeled by the application of a constant torque at the ankle joint. This choice is appropriate when the amplitude of the tracked target oscillations is small (5 cm in the simulation). A second active torque operating at the hip joint, but with an opposite sign, compensates for the growing inertial force that accompanies an increase in movement frequency, thus maintaining the system in balance. The amplitude of the second torque is not constant but increases exponentially with frequency until an asymptotic value is reached in the vicinity of the transition zone.

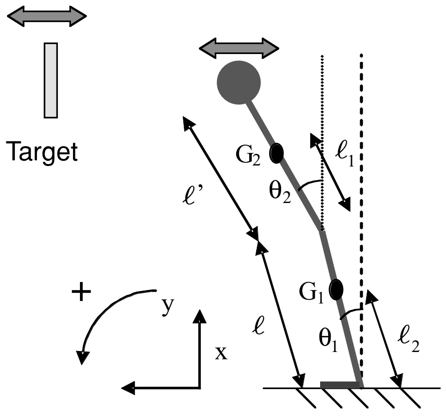


FIGURE 2. Double-inverted pendulum model of the human body during the simulated tracking task. Rotations of the two segments with respect to gravity are given by θ_1 (legs) and θ_2 (trunk). G_1 and G_2 refer to the position of the centers of mass of the two segments and are located at distances $\underline{l_1}$ and $\underline{l_2}$ from their axis of rotation. $\underline{l}$ and $\underline{l'}$ refer to the length of the two segments.

On the basis on these considerations, the differential equations for the motion of the system were computed, derived from Lagrange's equations:

$$\ddot{\theta}_1 + f_1(\dot{\theta}_1) + g_1(\theta_1) = I_1(\dot{\theta}_1, \theta_1, \dot{\theta}_2, \theta_2)$$
$$\ddot{\theta}_2 + f_2(\dot{\theta}_2) + g_2(\theta_2) = I_2(\dot{\theta}_1, \theta_1, \dot{\theta}_2, \theta_2)$$

where f_i (i = 1,2) is the damping function, g_i (i = 1,2) is the stiffness function and I_i (i = 1,2) is the coupling function between the two joints.

Simulations. In order to match the target oscillation amplitude in the experimental studies summarized above, torque amplitude of 15 N.m was chosen for the ankles. As a result of this choice, the torque amplitude at the hip joint needed to be greater than 5 N.m but smaller than 20 N.m in order to counterbalance the inertial forces while maintaining the amplitude of the head. Stiffness coefficients acting at the joints were estimated at 1100 N.m.rad^{-1} for the ankles and

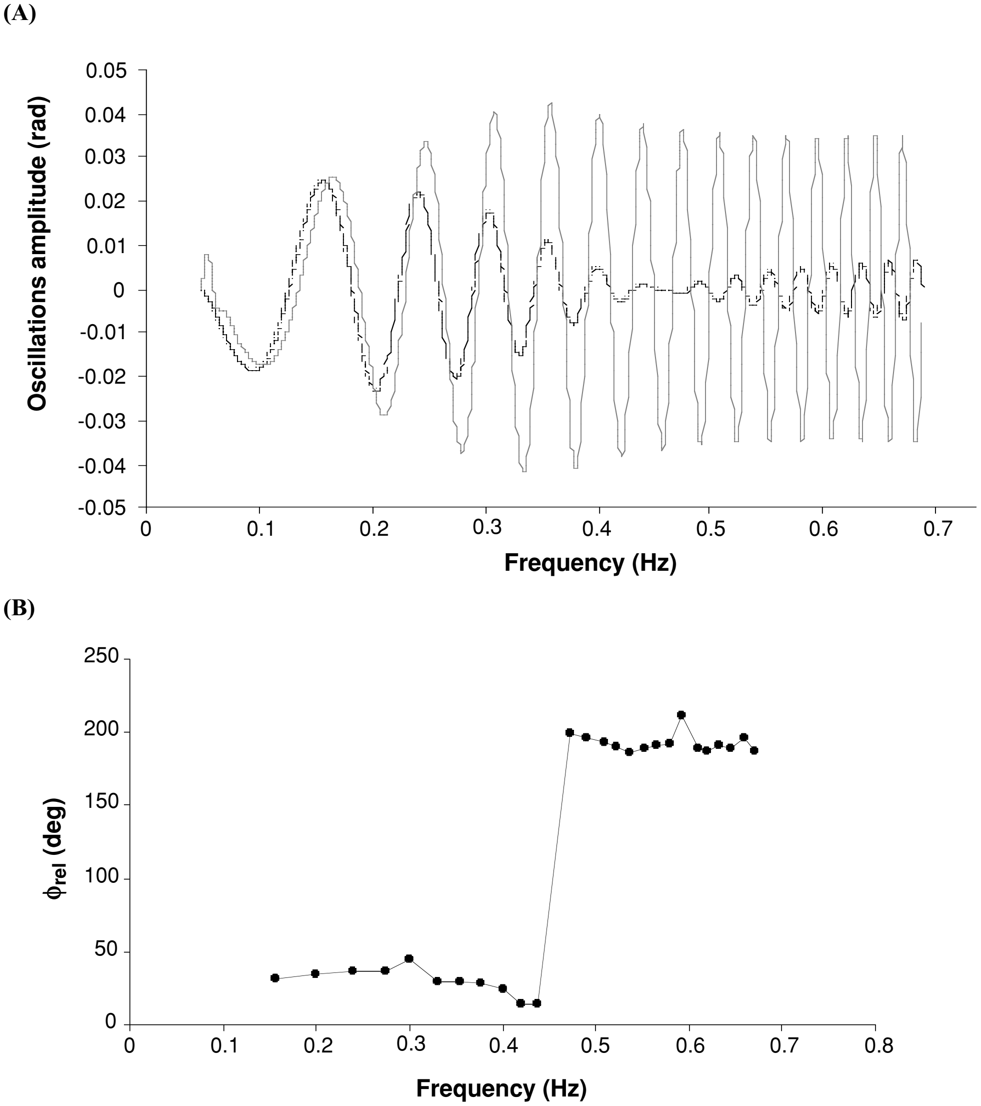


FIGURE 3. Transition region for one numerical simulation (Up condition), showing angular ankle and hip amplitudes (in radians, Figure 3a) as well as the (point-estimate) relative phase ϕ_{rel} (Figure 3b) as a function of target frequency. Sustained in phase motion at low frequency, anti-phase motion at high frequency, and a transition from an in-phase to anti-phase at $f =$ 0.45 Hz can be observed. Parameters for this simulation were $\Gamma_1 = 15$ N.m, $\Gamma_2 = 10$ N.m, weight = 70 kg, size = 1.75 m.

300 N.m.rad^{-1} for the hips according to the literature (Farley & Morgenroth, 1999, Stefanyshyn & Nigg, 1998, Weiss, Hunter & Kearney, 1988). The simulations described below were obtained for a typical subject of intermediate height (175 cm) and weight (70 kg). Local masses and positions of local centers of were respectively provided by Winter (1990) and Le Veau (1977).

The main behavior resulting from the numerical simulations (performed with Matlab©) is shown in Figure 3, representing ankle and hip oscillations as a function of frequency. For low frequencies, the model exhibited an ankle-hip relative phase close to 0°, and an ankle-hip relative phase close to 180° for large frequency values. The system abruptly switched from an in-phase mode to an anti-phase mode at a specific frequency value (0.45 Hz in Figure 3). Another interesting outcome of the model is the decrease in amplitude that accompanied the increase in frequency, toward zero at the transition point, with a reverse increase in amplitude after the transition point (i.e., after emergence of the anti-phase mode). This typical behavior was induced by the segmental inertia of the coupled components.

This simple mechanical model of the human body captures two of the essential properties that have been observed in standing humans involved in suprapostural activities (e.g., Bardy et al., 2002): the presence of two attractors for the relative phase of ankle-hip coordination, and a frequency-induced transition between attractors as target frequency increases. The model has been developed to reproduce *critical fluctuations*, that is, the increase in the standard deviation of ϕ_{rel} in the vicinity of the transition, *hysteresis*, that is, the tendency of a system to remain in its current basin of attraction as a control parameter moves through the transition region, and *differential critical slowing down* far and close to the transition (Fourcade, Bardy & Roudeix, 2005). The success of this model suggests that it is possible, and we would say necessary, to root the general organizational principles accompanying movement control into the biomechanical (or neuro-physiological) substrates of specific biological systems, such as the postural system. It also suggests that an intermediate position on the structural-phenomenological line (c.f., Beek et al., 1998) can be a useful route to follow for modeling human movement.

THE LEARNING OF NEW POSTURAL PATTERNS

The experimental and modeling efforts reported above offer evidence for the existence of self-organization in whole-body coordination. They encourage further examination of the possibility that the interactions between the components of the postural system may be understood through the physics of non-equilibrium processes. In our initial study of transitions between postural coordination modes (Bardy et al., 2002) the two modes that we observed emerged spontaneously (i.e., without instruction). In this section, we examine a complementary question of our research agenda on postural dynamics, related to how new postural modes are learned (see Faugloire, 2005; for a detailed treatment). We suggest that learning a new mode of postural coordination depends heavily on the competition between the dynamics of the new, to-be-learned pattern and the dynamics of pre-existing, stable postural patterns. We briefly describe the results of a study in which participants learned a new multi-joint postural coordination (Bardy, Faugloire, & Stoffregen, 2005).

In bimanual coordination, Zanone and Kelso (e.g., 1992; 1997) have elaborated a dynamical account of motor learning, based on the fact that the process of learning a new coordination pattern interacts with pre-existing states of the motor system. This interaction consists mainly of two phenomena. First, preferred and stable coordination tendencies systematically affect the ability to learn a new pattern: The more stable the initial states, the more difficult the learning of the new pattern. Second, learning a new mode changes the entire dynamics of the motor system, and can destabilize pre-existing (and previously stable) modes. In bimanual coordination, the two facets of this interaction have been explored in several studies (e.g., Fontaine, Lee & Swinnen, 1997; Lee, Swinnen & Verschueren, 1995; Smethurst & Carson, 2001; Wenderoth & Bock, 2001; Zanone & Kelso, 1992; 1997; Kelso & Zanone, 2002). Both convergences and divergences between theoretical predictions and experimental results have been found. As far as we know, only bimanual systems (fingers or arms) have been used to address these questions, and in terms of theory-testing the literature is cruelly lacking data from other motor systems. Formally, the dynamics of learning a new coordination should follow the same principles, irrespective of the effector system involved. However, the postural system (PS) is very different from the bimanual system (BS), in terms of the number of degrees of freedom involved (few for BS, many for PS), the eigenfrequency of the components involved (identical for BS, different for PS), and the type of coupling (perceptual for BS, perceptual and inertial for PS). Thus, the postural system may be a good candidate to test the generality of a dynamic theory of learning.

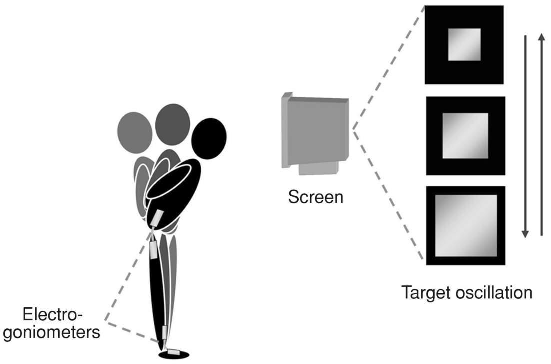


FIGURE 4. The visual tracking task used for the pre-test and post-test. Participants were instructed to follow with the head the antero-posterior oscillations of a moving target.

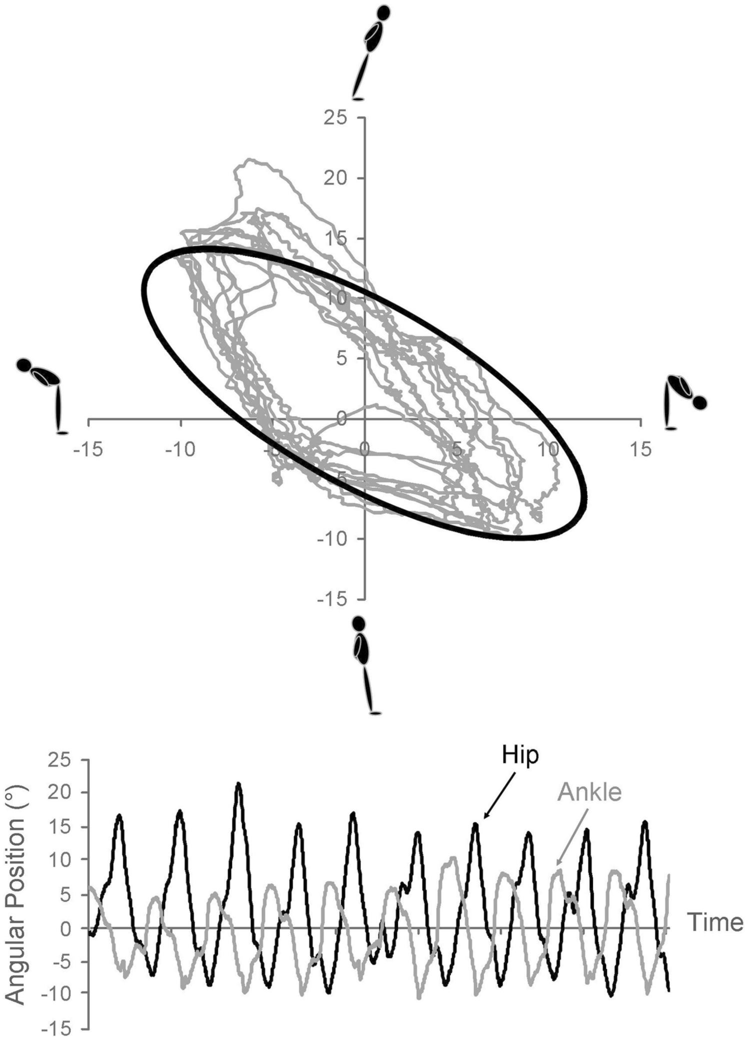


FIGURE 5. Top: Feed-back given to participants after every third trial showing the discrepancy in the ankle-hip plane (state space, or Lissajous plot) between the current pattern and the pattern to be learned (135°); Bottom: Hip and ankle movements (in degrees) over time during the production of a 135° relative phase pattern.

We recently carried out experiments in order to examine the learning of new postural patterns and its consequences on the stability of spontaneous, initial patterns (Bardy et al., 2005). We chose a relative phase of 135° between ankle and hip movements. A relative phase of 135° does not occur spontaneously in stance (so far as we know), has not been observed previously in our studies, and seems learnable. In one experiment, we investigated interactions between the process of learning the 135° pattern and the pre-existing anti-phase pattern. In our second experiment, we investigated how the process of learning the 135° pattern affected the pre-existing in-phase pattern. We also tested the durability of the pattern modifications, using a retention test conducted one week after the learning session.

Experiment 1 consisted of three sessions, using a pre-test/post-test design realized over two consecutive days. In the first session, or pre-test, participants ($N = 11$) performed the supra-postural task illustrated in Figure 4, with the instruction to maintain a constant distance between the head and a visible target that oscillated in the anterior-posterior axis (see Bardy et al., 1999 for details). They performed four trials of 10 oscillations each. We measured angular displacements of ankle and hip joints with two electrogoniometers connected to a DATALINK interface (Biometrics, Inc.). The emerging coordination in performing the supra-postural task was called the *initial spontaneous coordination*, and was characterized by the (discrete) ankle-hip relative phase, ϕ_{rel}. Its standard deviation, $SD\,\phi_{rel}$, indicated the stability of the coordination. The frequency and the amplitude of target motion were chosen to produce an anti-phase pattern (the in-phase pattern was investigated in Experiment 2). The second part of the experiment was the learning session. Participants attempted to learn the 135° relative phase based on explanations and demonstrations, but with no target to track. The learning phase consisted of 30 trials of 10 oscillations each, 15 on the first day, and 15 on the second day. After every three trials, participants were given feedback indicating the discrepancy between the performed coordination and the to-be-learned pattern (Figure 5). Finally, in a post-test after the learning phase, we repeated the pre-test tracking task to assess the effects of learning on the stability of initial spontaneous patterns. Therefore, participants performed the supra-postural task (tracking the target) during the pre-test and post-test sessions, in between which they attempted to learn the new 135° pattern.

Experiment 2 repeated the same design, with the following changes. First, to examine the effect of learning on both the in-phase and anti-phase patterns, different groups of participants were tested with low frequency ($N = 5$) and high frequency ($N = 6$) target motion. Based on previous studies using the supra-postural task (Bardy et al., 1999; 2002; Marin et al., 1999), we expected that low target frequency (0.25 Hz) would induce in-phase ankle-hip coordination while high target frequency (0.65 Hz) would produce an anti-phase pattern. The second change compared to Experiment 1 was that the learning phase was interrupted by four intermediate test sessions, which were introduced at regular intervals. This was done to observe the evolution of the pre-existing coordination patterns during the learning of the new pattern. Third, the experiment was conducted over three days, and the number of practice trials during the learning session was increased to 50 (10 the first day, and 20 the second and the third day). Finally, a retention test completed one week after the end of practice was used to estimate the durability of the changes observed in spontaneous and learned patterns.

The two experiments revealed several important results.

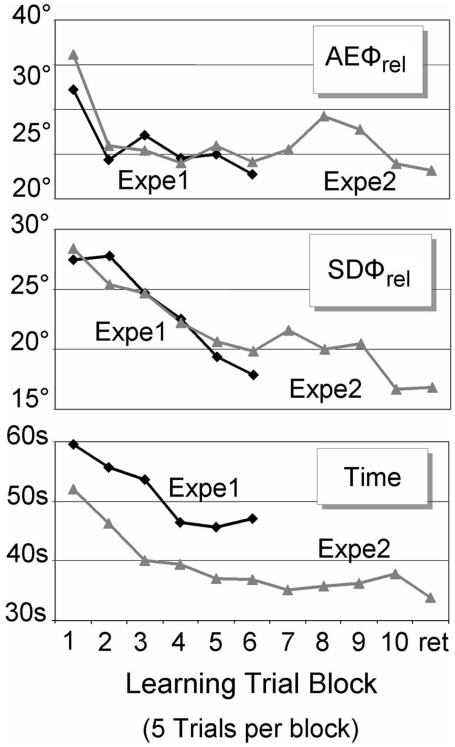
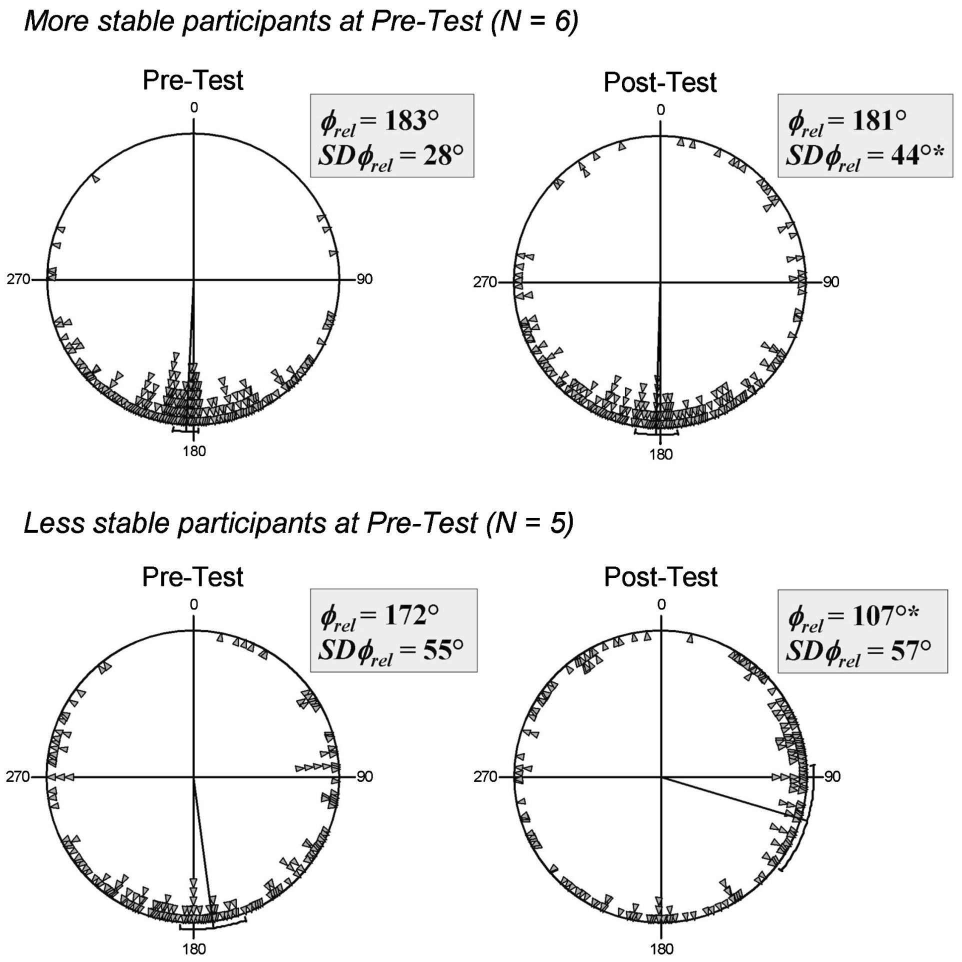


FIGURE 6. Mean results for the learning group in the two experiments (Expe 1 and Expe2). Evolution of absolute error *AE* for relative phase ϕ_{rel}, standard deviation of relative phase $SD\phi_{rel}$, and movement time during learning. Ret indicates the retention test.

Learning Session. We observed a decrease over trial in the absolute error, *AE* (discrepancy between produced ϕ_{rel} and learned ϕ_{rel}), a decrease in $SD\ \phi_{rel}$, and a decrease in the time taken to perform a trial (i.e., movement time *MT*). All changes were significant. Figure 6 presents the evolution of these three variables for the two experiments. The observed evolution of accuracy, stability, and movement time confirms that participants learned the requested 135° coordination with practice.

Influence of Initial Stability of Spontaneous Patterns on Learning. No significant correlation was found between $SD\ \phi_{rel}$ of the initial spontaneous pattern and the three variables capturing learning (*AE*, $SD\ \phi_{rel}$, or *MT*), neither at the beginning nor at the end of the learning session. Thus, contrary to what has been found in bimanual studies (Zanone & Kelso, 1992), we did not find any relation between initial stability and learning rate.


More stable participants at Pre-Test (N = 6)

Less stable participants at Pre-Test (N = 5)

FIGURE 7. Polar distributions of relative phase values at pre-test (left) and post-test (right) in Experiment 1, showing differences in pattern destabilization due to learning. (Top): Values of the most stable participants showing a significant change$^{(*)}$ in standard deviation and confidence interval around the mean relative phase between pre- and post-test; (Bottom) Values of less stable participants showing a change in relative phase values between pre- and post-test.

Differential Influence of Learning a New Coordination on Spontaneous Postural Modes. Between the pre-test and the post-test (and between the pre-test and the intermediate tests in Experiment 2), we observed important changes in ϕ_{rel} as well as in $SD\ \phi_{rel}$, providing evidence for the destabilization of initial spontaneous pattern due to learning. However, these changes did not occur equally across all participants and appeared to be dependant upon initial stability (i.e., $SD\ \phi_{rel}$ at pre-test). Indeed, in Experiment 1, participants with high initial stability ($N = 6$) presented a loss of this stability between the pre-test and the post-test, whereas participants with low initial stability ($N = 5$) showed a shift in relative phase toward the learned pattern. In other words, participants modified either the stability of their spontaneous coordination, or the ankle-hip coordination itself, depending on the stability of the spontaneous coordination (Figure 7). The difference in the nature of the destabilization was also observed for the anti-phase pattern of Experiment 2 (i.e., high frequency group). Participants from the high frequency group (0.65 Hz) presented three different types of destabilization (Figure 8): the most stable participants ($N = 2$) did not show any destabilization

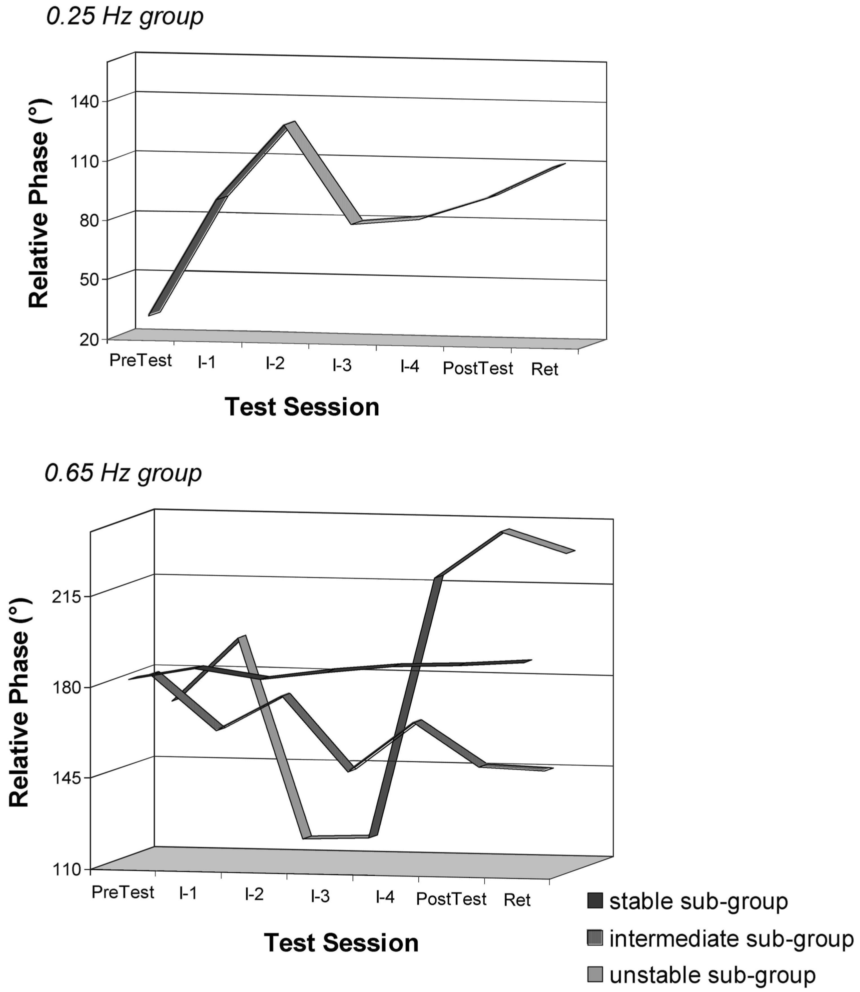


FIGURE 8. Destabilization due to learning in Experiment 2. Changes in the relative phase ϕ_{rel} over the seven tracking tests (Pre-test, I-1 to I-4: inter-test 1 to inter-test 4, Post-test, Ret: retention test), for the 0.25 Hz group (Top) and the three sub-groups of the 0.65 Hz group (bottom).

of the initial spontaneous pattern ($\phi_{rel} = 183°$ at the pre-test and 191° at the post-test); the two intermediately stable participants at pre-test showed a shift in the spontaneous relative phase toward the learned pattern ($\phi_{rel} = 182°$ at the pre-test and 148° at the post-test); the less stable participants ($N = 2$) exhibited the same shift toward the learned pattern, before a clear shift toward its symmetric pattern, i.e., 225° ($\phi_{rel} = 168°$ at pre-test and 236° at post-test). All participants from the low frequency group (Figure 8) evidenced a shift in the coordination ($\phi_{rel} = 31°$ at pre-test) in the direction of the learned pattern ($\phi_{rel} = 93°$ at post-test). As we can see in Figure 8, the changes recorded for the low and high frequency groups between pre- and post-tests were again observed at the retention test, suggesting that these changes were relatively permanent.

Conclusion

To some extent, the present results echo findings from research on bimanual coordination (e.g., see Faugloire, 2005 for a recent review). First, we found that it was possible to learn a new pattern of relative phase, and that learning was fast. Learning was characterized by both an increase in accuracy and a decrease in variability (e.g., Fontaine et al., 1997; Lee et al., 1995; Wenderoth & Bock, 2001; Zanone, & Kelso, 1992). The fact that learning was similar across very different systems (the bimanual system, the postural system) reinforces the idea of motor equivalency, the idea that the acquisition of new coordination patterns follows a set of general laws (Bernstein, 1967, Newell, 1996). Second, learning a new (self-paced) 135° coordinative mode was associated with destabilization of postural coordination modes that were assembled in support of the externally-paced tracking task. This destabilization was fast (after 30 learning trials in Experiment 1 and only 10 trials in Experiment 2), suggesting that in learning, stabilization and destabilization are intertwined phenomena, which can occur simultaneously rather than successively. It was also durable, as shown by the retention test.

The present results, together with the modeling effort reported in this chapter, support the conjecture that in-phase and anti-phase patterns observed during standing are emergent properties of the interaction between the natural tendencies of the postural systems and the external and internal constraints that shape coordination dynamics (e.g., Bardy, 2004, Faugloire, Bardy, Merhi & Stoffregen, 2005). The presence of appropriate constraints—not only including environmental or individual constraints but also task goals, such as the instruction to learn a novel pattern—is a prerequisite for the emergence of specific coordination patterns. Some evidence in favor of the idea that in coordination dynamics symmetry is preserved across the learning process has been found, at least in two participants (see Figure 8) exhibiting a shift toward a coordination pattern (225°) that was symmetrical (with respect to the 180° relative phase pattern produced initially) to the pattern that they were attempting to learn (135°). Similar effects have been found in the context of bi-manual coordination (e.g., Zanone & Kelso, 1997), suggesting that for these two participants (at least), the underlying symmetry of the attractor landscape was preserved during postural learning. Such an effect would confirm the abstract, and therefore transferable, nature of learning. The extent to which these patterns of coordination are abstract and transferable will be addressed in future research, with specific transfer experiments between postural and bimanual coordination.

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