Journal of Motor Behavior, 2007, Vol. 39, No. 4, 326–334

On Perturbation and Pattern Coexistence in Postural Coordination Dynamics

Benoît G. Bardy
Laboratoire Efficience et Déficience Motrices
Université Montpellier I
and Institut Universitaire de France, Paris

Olivier Oullier
Laboratoire de Neurobiologie Humaine UMR 6149
Université de Provence
Marseille, France

Julien Lagarde
Laboratoire Efficience et Déficience Motrices
Université Montpellier I, France

Thomas A. Stoffregen
Affordance Perception-Action Laboratory
University of Minnesota, Minneapolis

ABSTRACT. In studies of postural control, investigators have used either experimentally induced perturbations to stance or unperturbed stance. The distinction between perturbed and unperturbed stance has gained renewed importance in the context of in-phase and antiphase coordination of the hips and ankles. Several contributions have replicated the findings published over the past decade, suggesting the possibility of a unified view of postural control. However, any proposed unified view depends on how so called perturbed and unperturbed are defined. The authors argue that, to date, there is no explicit and general definition of those terms. The main reason is that all perturbations are relative and depend on appropriate frames of reference for perception and action. Arguments about empirical or theoretical unification of perturbed and unperturbed stance are premature.

Keywords: coordination dynamics, perturbation, postural control

The human body is a multijoint system that offers a potentially unlimited number of combinations of motion at different joints (Bernstein, 1967). In addition to offering multiple degrees of freedom, the body oscillates spontaneously and continuously at low frequency and low amplitude around the direction of balance (Riccio & Stoffregen, 1988; Yoneda & Tokumasu, 1986). The resulting high-order complexity of the postural system—and the interaction between its components and the constraints that are applied to it—generates a large amount of variability at different levels of observation (Newell & Corcos, 1993). Controlling such a complex system is therefore a difficult enterprise, but one that can be greatly facilitated by reduction of its dimensionality (Kay, 1988). Nashner (1976; Nashner & McCollum, 1985) first proposed that, among the many possible relations between joints or muscles, the maintenance of stance commonly relies on a small number of postural strategies. For Nashner, those strategies depend on *muscular synergies*, which he defined as patterns of muscle activation stored in the central nervous system (CNS) that reduce the dimensionality of the postural system by enabling it to focus on relationships between the muscles involved in the movement of the ankles and the hips. The concept of ankle and hip strategies has since met with wide acceptance (e.g., Nashner & McCollum).

Although widely accepted, the existence of postural strategies has been questioned from the perspective of coordination dynamics (for detailed discussions, see Bardy, 2004; Bardy, Marin, Stoffregen, & Bootsma, 1999). Inspired by dynamical systems theory (Kelso, 1995; Turvey, 1990) and by synergetics (Haken, 1983), postural coordination dynamics has emerged as an alternative way of understanding the coordination of multiple body segments in the control of stance (for a review, see Oullier, Marin, Stoffregen, Bootsma, & Bardy, 2006). Postural coordination dynamics has been embraced by many students of postural control (e.g., Bardy et al., 1999; Buchanan & Horak, 1999; Dijsktra, Schöner, Giese, & Gielen, 1994; Faugloire, Bardy, Merhi, & Stoffregen, 2005; Ko, Challis, Stitt, & Newell, 2003; Marin, Bardy, & Bootsma, 1999; Martin, Cahouët, Ferry, & Fouque, 2006; Oullier, Bardy, Stoffegen, & Bootsma, 2002; Schöner, 1991; Stirling & Zakynthinaki, 2004). In that approach, postural coordination patterns are considered as attractors, and transitions between patterns are thought to be governed by principles of self-organization. Bardy et al. identified two stable patterns of coordination between the hips and ankles (a) the in-phase mode (with hip–ankle relative phase about 20°)[1] and

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Correspondence address: Benoît G. Bardy, Institut Universitaire de France, and Laboratoire Efficience et Déficience Motrices, Université Montpellier-1, EDM - UFR STAPS, 700, av du pic Saint Loup, 34090 Montpellier, France. E-mail address: benoit.bardy@univ-montp1.fr

(b) the antiphase mode (with a relative phase of about 180°). Those patterns differ from the ankle and hip strategies both conceptually and empirically (cf. Balasubramaniam & Wing, 2002; Oullier et al., 2006).

Creath, Kiemel, Horak, Peterka, and Jeka (2005) recently documented the coexistence of in-phase and antiphase postural patterns. In their experiment, participants stood upright, with eyes closed, on three different surfaces: a rigid, stationary surface, a stationary foam surface, and a sway-referenced platform. In the sway-referenced condition, anteroposterior (AP) rotation of the platform (around the ankle axis) was proportional to hip rotation in the AP direction. Creath et al. used *spectral analyses*—that is, the phase angle between trunk and legs estimated from cross-spectral density—to evaluate the coordination patterns underlying stance on the three surfaces. Their results indicated for all three surfaces that the body behaves like a multijoint pendulum with two coexisting modes: (a) an in-phase mode at low oscillation frequencies (below 1 Hz), with the relative phase between the trunk and the legs close to 0°, and (b) an antiphase mode at high oscillation frequencies (above 1 Hz), with the trunk–leg relative phase close to 180°. When inspecting the relative phase corresponding to the different frequencies detected in the power spectrum of the motion of the joints, an abrupt shift was observed between in-phase and antiphase during stance on the rigid and foam surfaces, whereas a more gradual change in coordination was observed on the sway-referenced platform because of an increasing phase lead of the trunk angle with respect to the leg angle at high frequencies. On the basis of those results, Creath et al. (p. 75) argued for the existence of "simultaneous co-existing excitable modes," both of which are always present and one of which may predominate (i.e., emerge) depending on the characteristics of the available sensory information, task, or perturbation. Creath et al. characterized their experimental method as not using perturbations to stance, and on that basis they claimed that their study "unifies the relationship between quiet and perturbed stance" (p. 79).

Creath et al. (2005) addressed an important aspect of postural control, namely, the formation (and dissolution) of postural patterns that underlie the fundamental act of maintaining nonstatic upright stance (Yoneda & Tokumasu, 1986). Their data documented two important phenomena: the existence of (a) functional hip rotation during stance and (b) coordinated movement of the hips and ankles in stance. Each phenomenon runs counter to a large body of literature in the field of postural control (cf. Horak & Nashner, 1986). On the basis of their findings, Creath et al. rejected the enduring hypothesis that the body behaves like a single-segment inverted pendulum during unperturbed stance (Gurfinkel, 1973; Horak, Nashner, & Diener, 1990; Krishnamoorthy & Latash, 2005; McCollum & Leen, 1989; Nashner & McCollum, 1985). We concur in that rejection. We believe, however, that in several respects the presentation and the interpretation of Creath et al. are misleading. In this article, we discuss three aspects of their presentation that we believe to be problematic.

Perturbed or Unperturbed Stance?

Two popular paradigms for the study of postural control are the *perturbation paradigm*, and the *nonperturbation paradigm.* In the perturbation paradigm, standing participants are exposed to experimentally generated stimuli that are expected to elicit a change in postural coordination, that is, a compensatory response. Put simply, the perturbation is an independent variable, and postural motion is a dependent variable. According to the literature on postural control, three major types of perturbations have been used for experimental purposes: (a) visual, such as real or simulated motion of the visible surroundings (Dijkstra et al., 1994; Lee & Lishman, 1975; Stoffregen, 1985); (b) tactile and proprioceptive, for example, plantar, muscle, or tendon vibration (e.g., Eklund, 1972; Kavounoudias, Roll, & Roll, 2001; Roll & Roll, 1988); and (c) mechanical, such as the displacement of the surface of support (e.g., Buchanan & Horak, 2001; Corna, Tarantola, Nardone, Giordano, & Schieppati, 1999; Ko et al., 2003; Nashner, 1976; Van Wegen, van Emmerik, & Riccio, 2002). The perturbation paradigm differs from the nonperturbation paradigm, in which there are no experimentally imposed perturbations.

Those definitions may seem clear and mutually exclusive, but there is an area of ambiguity between them. The ambiguity concerns manipulations that influence stance but do not include externally generated motion. Many investigators have varied the dynamic properties of the support surface, such as its length, friction, or rigidity. Some researchers have varied support surface properties while measuring hip–ankle coordination (Bardy et al., 1999; Krishnamoorthy & Latash, 2005; Marin, Bardy, Baumberger, Fluckiger, & Stoffregen, 1999; Oullier, Bardy, Stoffregen, & Bootsma, 2004; Stoffregen, Adolph, Gorday, & Sheng, 1997). The study of Creath et al. (2005) belongs in the latter category because they manipulated support surface rigidity. Should manipulations of that kind be considered as perturbations of stance? Creath et al. reviewed several studies of coordination between rotations at the hips and ankles in stance, including some work in which a suprapostural tracking task was used (Bardy et al., 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002).[2] Creath et al. (p. 76) argued, "all previous analyses of ankle and hip patterns involved a perturbation of some form." That statement begs the question of how perturbation is to be defined. In some studies (e.g., Oullier et al., 2002, 2004), participants viewed a moving target that oscillated along the line of sight and were instructed to move deliberately so as to maintain a constant distance between their head and the target (in some studies, they were asked to simply look at the moving target). If one defines *perturbation* as an externally generated stimulus that leads to a compensatory response, then the tracking task that was used in the studies of Bardy and her colleagues was a perturbation (Bardy et al., 2002). On the other hand, if a perturbation is an experimental manipulation that elicits an automatic or involuntary postural response, then their tracking task was not a perturbation.

The issue of definition is further complicated by the fact that manipulations that do not include externally imposed motion may nevertheless be considered as perturbations. Changes in the rigidity or friction of support surfaces can be construed to perturb stance because they lead to changes in postural motion (for examples in the context of hip–ankle coordination, see Marin, Bardy, Baumberger, et al., 1999). By the same logic, eye closure (as used by Creath et al., 2005) can also be interpreted as a perturbation. It is well known that stance with the eyes closed differs from stance with the eyes open (Travis, 1945; Krishnamoorthy & Latash, 2005). Does the use of eye closure constitute a perturbation? At a minimum, the fact that participants' eyes were closed in all conditions of the Creath et al. study means that those results bear an uncertain relation to stance (perturbed or otherwise) when the eyes are open. Creath et al. did not state whether they considered their use of nonrigid surfaces and moving-platform posturography to constitute perturbations of stance. Their silence highlights the absence of a clear, widely accepted definition of perturbation in the literature on postural control. Creath et al. implicitly asserted that their use of eye closure did not constitute a perturbation of stance, but, as our discussion shows, that interpretation is also open to question.

The question of how we should define perturbations to stance has gained new relevance following results of recent research that led us to question the classical concept of quiet stance. In many studies, participants were instructed only to stand comfortably or stand as still as possible. On the basis of those instructions, researchers often have assumed that the control of posture was the only activity in which the participant was engaged or that any other activities were irrelevant to how posture was perceived and controlled. That assumption reflects the traditional belief that the main (perhaps the sole) purpose of postural control is to maintain balance (i.e., avoid falling). In a wide range of recent studies from a variety of theoretical perspectives, however, investigators have made it clear that the perception and control of upright stance are easily influenced by manipulations of the participants' suprapostural task, even when such tasks have no obvious relevance to the maintenance of stance (e.g., Woollacott & Shumway-Cook, 2002). Stoffregen, Pagulayan, Bardy, and Hettinger, (2000; Stoffregen, Smart, Bardy, & Pagulayan, 1999) have shown that the influence of suprapostural tasks on postural control tends to be functional. The amplitude of body sway is influenced by the precision with which the eyes must be controlled in executing visual tasks, for example, searching text, tracking moving objects, and fixating nearby (as opposed to distant) objects. Stoffregen et al. (2000) asked participants to switch between suprapostural tasks during trials (from letter searching to viewing of a blank target, or vice versa) and found that participants reorganized postural control, online, in response to those task changes. In that study, there was no imposed stimulus motion of any kind; all targets were stationary. Manipulations of suprapostural tasks clearly influence the manner in which posture is controlled. Should such manipulations be construed as perturbations to stance? Are such manipulations meaningfully different (in terms of their effects on postural control) from eye closure or from stance on a nonrigid surface?

Our discussion reveals that the eye-closure, rigidity, and moving-platform manipulations used by Creath et al. (2005) all constitute perturbations to stance under some definitions of perturbation. Given that different definitions of perturbation are possible, it may seem that an effort should be made to reach consensus on a single definition. We believe, however, that no single definition of perturbation can succeed. In our view, the definition of perturbation is not fixed, but varies across situations in a context-dependent way. A given factor may act as a perturbation to stance in some situations but have no influence on stance in other situations. An external stimulus to the postural system counts as a perturbation only if the person's goal is to stabilize posture relative to that stimulus. In the natural environment (i.e., outside the laboratory), many things may be perceived to move in various ways at any given time. Consider a person standing at a busy street corner in a large city. There can be visible relative motion between the person and any number of things: Clouds in the sky, branches waving in the breeze, cars on the street, and different people moving in different directions are some examples. When the person looks in a given direction, several different relative motions may be visible simultaneously. One could argue that each of those motions constitutes an independent visual perturbation to stance. However, most such motions will have no effect on the person's sense of their own orientation or on their postural control actions. That anecdotal description has obtained support in some laboratory experiments. Here, we review two of those experiments.

Shockley, Santana, and Fowler (2003) asked pairs of participants to converse with each other or with other people. When members of a pair conversed with each other, their postural activity became coordinated. When each member of the pair conversed with a different person (two experimenters), the postural activities of the members of the pair were not coordinated. In each case (when the pair conversed with each other, and when each member conversed with someone else), members of the pair could see and hear each other. Thus, each member could see and hear the other member of the pair. We can argue, then, that the visual and acoustic correlates of conversation acted as perturbations to stance under some conditions (when members of a pair conversed with each other), but that those same correlates did not perturb stance under other conditions (when each member of a pair conversed with someone else). We conclude that the definition of perturbation in that study varied depending on each person's goals (i.e., the individual with which they were conversing).

For a very different example, consider one of the studies of hip–ankle coordination in the control of stance. Oullier et al. (2002) placed standing participants in a moving room oscillating along the line of sight. They varied the frequency at which the room oscillated. They separately varied the behavioral goals. In some cases, participants were asked simply to look at the interior walls of the room (the looking task). In other cases, participants were asked to deliberately move back and forth to maintain a constant distance between the front wall of the room and their head (the tracking task). Motion of the room was identical for the looking and tracking tasks, but participants' behavior was strongly influenced by the variation in task goals. For instance, the coupling between room motion and head motion decreased during looking compared with that in tracking, whereas hip and ankle rotations could be captured by in-phase and antiphase coordination in both cases. The extent to which room motion perturbed head–room coupling, on the one hand, but did not perturb hip–ankle coordination, on the other, differed solely as a function of the variation in behavioral goals (additional details are provide in the next section of this article).

Such effects can be understood, at a general level, in terms of external frames of reference for perception and action. When conversing with another person, it is useful to control some aspects of body movement relative to the conversational partner (e.g., mutual gaze, remaining face to face). Thus, the partner becomes a frame of reference for perception and action. The results of the study of Oullier et al. (2002) indicated that people are not obliged to control every aspect of their behavior with respect to a given frame of reference. Different aspects of behavior may be coupled to a given frame of reference in different ways, depending on one's goals. For that reason, we argue, there can be no fixed, general definition of perturbation.

The number and nature of reference frames is constrained by relativistic physics. In a relativistic universe, there is no absolute position and there is no absolute motion. Position and motion can be defined (and, by implication, perceived and controlled) only relative to frames of reference. Motion relative to one referent (e.g., a conversational partner) can be independent of motion relative to another (e.g., a nearby stranger). When we perceive and control our actions relative to a given referent, how we move relative to some other referent may be irrelevant to the success of our actions, in which case motion relative to that other referent should not perturb our actions. Stoffregen and Bardy (2001, Sections 4 and 5) discussed at length frames of reference for perception and action, relativistic physics, and their consequences for the theory and for research on perception and action. One implication of our analysis is that a given experimental manipulation may or may not function as a perturbation to stance, depending upon the experimental design and instructions. In part for that reason, we believe that the study of Creath et al. (2005) falls into an area of ambiguity between perturbed and unperturbed stance. That uncertainty, in turn, casts doubt on the extent to which their study can be said to unify the literatures on perturbed and unperturbed stance.

There are similar uncertainties in the literature about the relation between cognition and postural control. Does the use of a visuospatial task or a reaction time task performed simultaneously with a postural task constitute a perturbation of stance (e.g., Huxhold, Li, Schmiedek, & Lindenberger, 2006)? Does the fear of standing on an elevated support surface constitute a perturbation (Carpenter, Frank, & Silcher, 1999? Attentional focus, anxiety, and cognitive factors are known to influence both sway variability and postural coordination, but do we need to consider them as perturbations of the postural system? Last, how should we consider the effects on stance and posture of endogenous factors such as pregnancy (Butler, Colon, Druzin, & Rose, 2006), age (e.g., Forth, Metter, & Paloski, 2007), autism (e.g., Minshew, Sung, Jones, & Furman, 2004), or Parkinson's disease (Bloem, Grimbergen, van Dijk, & Munneke, 2006) All those examples suggest the relative nature of perturbation and its context dependency and, therefore, undermine the idea that there can be any single, general definition of perturbation in the context of stance.

Coexistence of Postural Coordination Patterns

Creath et al. (2005) rejected the idea that upright stance can be viewed as a single-segment inverted pendulum. The central basis for that rejection was their empirical finding of the coexistence of two postural coordination patterns. Creath et al. claimed that that result was novel, that is, that theirs is the first study in which it was found. We dispute that claim. Creath et al. did not discuss a substantial body of conceptual discussion and empirical research on that topic. In the last decade or so, numerous theoretical and experimental studies have enriched the literature on postural control and postural coordination dynamics, and have provided a robust basis for rejection of the inverted-pendulum analogy (for reviews, see Bardy, 2004; Oullier et al., 2006). The results of several studies have shown that in-phase and antiphase postural patterns emerge out of the interaction of multiple constraints, including body properties (Bardy et al., 1999), surface properties (Marin, Bardy, Baumberger, et al., 1999; Oullier et al., 2004), expertise (Marin, Bardy, & Bootsma, 1999), and task properties (Oullier et al., 2002, 2004). They exhibit persistence and changes that are characteristic of nonlinear systems (Bardy et al., 2002). Moreover, one learns those patterns by modifying the intrinsic dynamics of the postural system (Bardy, Faugloire, & Fourcade, 2006; Faugloire et al., 2005). The results of the just-mentioned experiments are inconsistent with the single inverted-pendulum analogy, a point that has been made explicitly in each of those articles. The observed similarities between postural phase transitions (in humans) and nonbiological phenomena argue for the existence of general principles governing pattern formation and flexibility in complex systems (Haken, 1983; Kelso, 1995). Moreover, some of those studies provide direct evidence for what Creath et al. (2005) referred to as *simultaneous coexisting excitable modes of coordination*. For instance, Bardy et al. (2002) observed the existence of hysteresis in transitions between in-phase and antiphase patterns of hip–ankle coordination. That effect revealed that the postural system adopts either the in-phase or the antiphase mode for a given value of the control parameter, depending on previous history, including initial conditions. Hysteresis illustrates the tendency of the postural system to be multistable. One can more clearly demonstrate multistability by setting the initial condition within the range of values of the control parameter for which the hysteretic loop is observed; in such a configuration, the system will be able to choose between the in-phase and the antiphase attractors. Figure 1 (adapted from Bardy et al., 2002) represents the relative phase between the ankle and the hip plotted against the oscillating frequency of a visual target in two representative trials performed by the same participant. The gray line shows what happened when the frequency was increased during the trial, and the black, dashed line shows what happened when it was decreased. In the hysteresis region (i.e., between 0.25 and 0.4 Hz), both coordination patterns (in-phase and antiphase) were adopted, depending on conditions at the beginning of the trial (i.e. high or low frequency).

The findings of Bardy et al. (2002) run counter to the single-segment, inverted-pendulum analogy. Similar findings were reported by Oullier et al. (2002), who documented the emergence of in-phase and antiphase modes in a task in which participants standing in a moving room were instructed merely to look at (as opposed to deliberately track) a target attached to the room. Oullier et al. changed the frequency of room motion within trials to induce a transition in hip–ankle coordination. The room moved at a constant (peak-to-peak) amplitude of 4 cm, so the stimulus motion was in the range of natural body sway amplitude. Those experiments, along with others that were also not discussed by Creath et al. (2005), clearly demonstrated that people can adopt both the in-phase and the antiphase patterns for the same sway frequencies (between 0.45 and 0.60 Hz) whether they are simply looking at the motion of a moving target (Figure 2A) or are tracking it with the head (Figure 2B). There is therefore a range of frequencies over which the postural system is bistable, that is, for which the two postural coordination patterns coexist in the phase space.

How Shall We Quantify Postural Coordination Dynamics?

Creath et al. (2005, p. 79) questioned the method Bardy et al. (2002) used to compute ankle–hip relative phase, as follows: “We question whether the peak-picking method of analysis used by Bardy et al. fully characterizes the behavioral modes. Peak picking essentially acts as a filter and characterizes the mode that is most closely aligned with the visual stimulus, ignoring significant power at other frequencies.” Computation of relative phase via the peak-picking method (Zanone & Kelso, 1992, 1997) carries less information than does continuous computation in the position–velocity phase

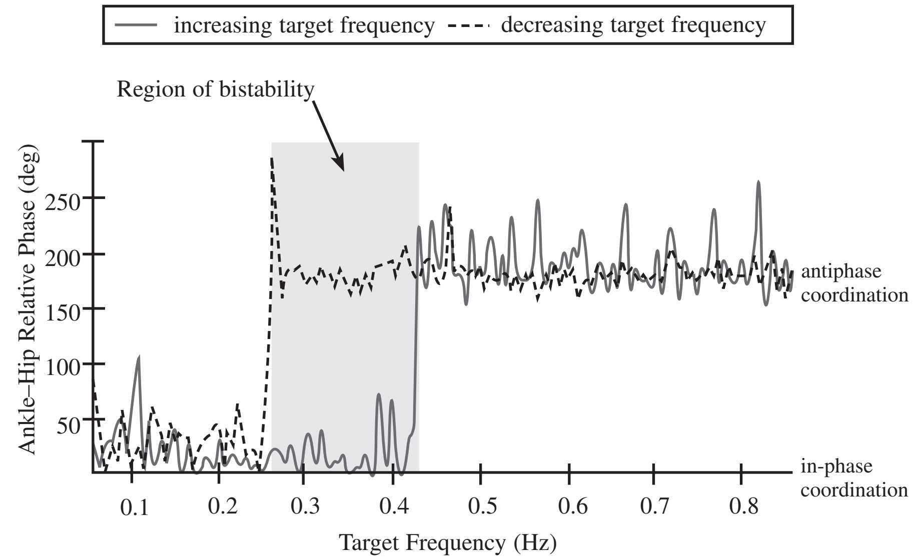

FIGURE 1. Coexistence of in-phase and antiphase patterns during a tracking task (individual participant). Participants were asked to use head motion to track 10-cm (peak-to-peak) oscillations of a visual target while the authors measured coordination between the ankle and the hip. The gray line (plain) represents a trial in which the frequency of oscillation increased, whereas the black line (dashed) represents a trial in which the frequency of the target decreased. The shaded region represents the region of bistability, that is, the region in which both coordination patterns coexisted.

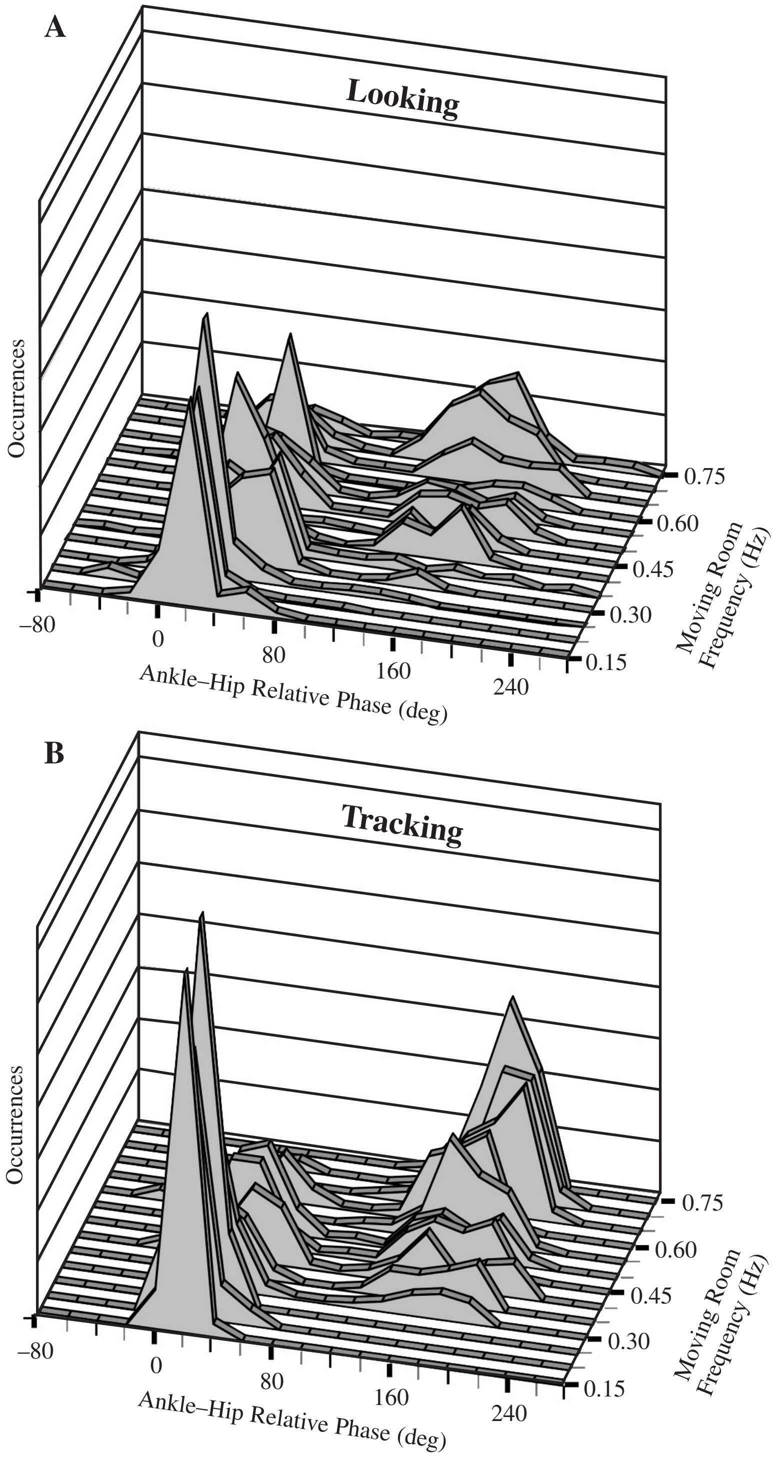

FIGURE 2. Coexistence of in-phase and antiphase patterns when participants ($N = 14$) looked at or tracked a target. Distribution of ankle–hip relative phase values (in 20° frequency bins) as a function of room motion frequency in (**A**) the looking condition (participants simply looked at the target) and (**B**) the tracking condition (participants tracked the oscillations of the target, as in Figure 1). The authors collapsed relative phase values across directional changes (increasing or decreasing frequency) to create these figures (adapted from Figure 5 of O. Oullier, B. G. Bardy, T. A. Stoffregen, & R. J. Bootsma (2002). Postural coordination in looking and tracking tasks. *Human Movement Science, 21,* 147–167. Copyright 2002 Elsevier.

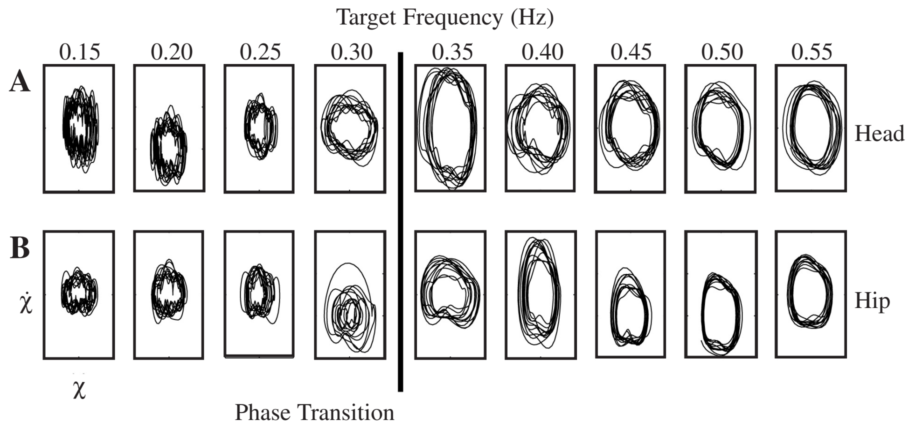

FIGURE 3. Limit-cycle behavior of head and hip movement. Phase portraits (position vs. velocity) of the trajectory of the head (**A**) and the hip (**B**) for each 10-cycle-long frequency plateau (from 0.15 Hz to 0.55 Hz, in 0.05-Hz increments). The data are taken from a single trial from Bardy et al. (2002). Note that during that trial, the phase transition from the in-phase to the antiphase pattern occurred at 0.35 Hz and was preceded by a loss of stability, which is clearly illustrated on the hip phase portrait at 0.30 Hz.

space (Scholz, 1993) or computation based on the Hilbert transform (Bendat & Piersol, 1985; Rosemblum & Kurths, 1998). We therefore accept the assertion of Creath et al. that the peak-picking method acts as a frequency filter.[3]

Although we agree on that methodological point, which has already been addressed at length in the context of human movement (e.g., Fuchs, Jirsa, Haken, & Kelso, 1996), we do not accept the conclusion drawn from it by Creath et al. (2005). They asserted, "the upright body does not behave like a limit cycle, even when oscillatory stimuli are imposed" (p. 79). The terms that they used to characterize posture, *in-phase* and *antiphase,* seem to imply that the units involved behave like limit cycles. From a theoretical point of view, that vocabulary (and the underlying methods used to compute phase) is justified only if the behavior is cyclical (Haken, 1983). In addition, the claim of Creath et al. does not appear to be compatible with recent empirical data (Bardy et al., 2002). As illustrated in Figure 3, regardless of the movement frequency imposed by the tracking task, the phase portraits reveal clear limit-cycle behavior for head and hip movements.

That observation confirms that the discrete computation of relative phase in Bardy et al. (2002) did not filter out the relevant information, that is, the nature of the postural transitions that occurred under a given regime of constraints and the evidence that both postural coordination patterns coexisted in the region of bistability. Although Lagrangian mechanical models of coupled inverted pendula can easily reproduce the existence of stables states and bifurcation under certain optimization principles (Bardy et al., 2006; Martin et al., 2006), they are unable so far to reproduce hysteresis and bistability. Observation of those hallmarks leads to the hypothesis that the transition between in-phase and antiphase resembles a saddle-node type of bifurcation (Kelso, Ding, & Schöner, 1992). The dynamics of transitions between coordination modes thus seem specific to the properties of the system and the level at which the system is analyzed (Oullier et al., 2006).

Conclusion

Creath et al.'s (2005) definition of perturbed and unperturbed stance is disputable, and after having reviewed the literature on that topic, we dispute it. We consequently reject the supposed novelty of their results. Their finding that ankle–hip coordination during unperturbed stance exhibits typical features of complex dynamical systems, such as stable states (in-phase, antiphase) and bifurcation, is a useful confirmation of previous work in this area. In broader terms, our discussion underscores the absence of explicit, consistent definitions of perturbed and unperturbed stance. Only when we have such definitions will it be possible to determine, without ambiguity, relations between results obtained using those two paradigms.

ACKNOWLEDGMENTS

Grants from Enactive Interfaces, a network of excellence (IST Contract No. 002114) of the Commission of the European Community (to B. G. Bardy and J. Lagarde), and from the Fondation de l'Académie des Sciences (to O. Oullier), and the National Science Foundation (BCS-0236627) to T. A. Stoffregen) supported the writing of this article. The authors are grateful to Viktor Jirsa and Gonzalo de Guzman for methodological discussions and for helpful comments on an earlier version of the manuscript.

NOTES

1. The departure from pure in-phase motion (0° relative phase) may result from frequency competition between oscillators that have different eigenfrequencies and from the mechanical coupling between upper and lower parts of the body (for details, cf. Bardy et al., 2002).

2. In this task, standing participants are instructed to track with the head the fore–aft motion of an oscillatory target, keeping the distance between target and head constant at all times.

3. Bardy et al. (1999) did not use a peak-picking algorithm to compute relative phase. Instead they used spectral methods that provided clear indications that during the tracking task the frequency of the target was the main one found in the ankle and hip oscillations.

Biographical Notes

Benoît G. Bardy is full professor of kinesiology at the Institut Universitaire de France and the Université Montpellier-1. His teaching and research activities concern motor control and coordination dynamics in general, as well as multimodal perception in real and virtual environments.

Olivier Oullier is an assistant professor in neuroscience at the Université de Provence (Marseille). He teaches coordination dynamics and neuroeconomics. In his research, he addresses social coordination dynamics of brain and behavior.

Julien Lagarde is a postdoctoral fellow at the Université Montpellier-1. His research covers coordination dynamics in brain and behavior, with an emphasis on multimodal integration and interpersonal coordination.

Thomas A. Stoffregen is a professor of kinesiology at the University of Minnesota and is a member of the graduate Faculties of Engineering, Human Factors, and Psychology. In his research, he focuses on perception and action in support of naturalistic, meaningful behaviors.

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Submitted June 3, 2006
Revised October 11, 2006
Second revision November 10, 2006