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# The effects of feedback format, and egocentric & allocentric relative phase on coordination stability[☆]

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## ABSTRACT

The stability of coordinated rhythmic movement is primarily affected by the required mean relative phase. In general, symmetrical coordination is more stable than asymmetrical coordination; however, there are two ways to define relative phase and the associated symmetries. The first is in an *egocentric* frame of reference, with symmetry defined relative to the sagittal plane down the midline of the body. The second is in an *allocentric* frame of reference, with symmetry defined in terms of the relative direction of motion. Experiments designed to separate these constraints have shown that both egocentric and allocentric constraints contribute to overall coordination stability, with the former typically showing larger effects. However, separating these constraints has meant comparing movements made either in different planes of motion, or by limbs in different postures. In addition, allocentric information about the coordination is either in the form of the actual limb motion, or a transformed, Lissajous feedback display. These factors limit both the comparisons that can be made and the interpretations of these comparisons. The current study examined the effects of egocentric relative phase, allocentric relative phase, and allocentric feedback format on coordination stability in a single task. We found that while all three independently contributed to stability, the egocentric constraint dominated. This supports previous work. We examine the evidence underpinning theoretical explanations for the egocentric constraint, and describe how it may reflect the haptic perception of relative phase.

## 1. Introduction

Coordinated rhythmic movement is a well-established laboratory task used to study the composition and organisation of perceptually controlled action. It requires the online (perceptual) coordination and control of multiple limbs. The structure of the behaviour is surprisingly rich, and it is simple enough to model in great detail (e.g. Beek, Peper, & Daffertshofer, 2002; Bingham, 2001; Bingham, 2004a, 2004b; Cattaert, Semjen, & Summers, 1999; Daffertshofer, Peper, & Beek, 2005; Haken, Kelso, & Bunz, 1985; Peper, Ridderikhoff, Daffertshofer, & Beek, 2004; Snapp-Childs, Wilson, & Bingham, 2011). In addition, there are some coordinations that are difficult to produce without practice, allowing us to study the acquisition of these actions (e.g. Wilson, Snapp-Childs, Coats, & Bingham, 2010; Zanone & Kelso, 1992a, 1992b, 1997).

The current study directly compares the effects of three factors on coordination stability; egocentrically defined relative phase, allocentrically defined relative phase, and the format of the allocentric feedback.

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[☆] All data and a preprint available at https://osf.io/z7c9q/.

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## 2. Relative phase

The primary factor that affects coordination stability is the target relative phase. When two oscillating limbs are at the same point in their cycle (phase) at the same time, this is 0° mean relative phase, or in-phase, and it is the most stable state. If the two limbs are at opposite points in their cycle at the same time, this is 180° mean relative phase, or anti-phase. This is also a stable state, although it is less stable than 0°/in-phase (e.g. if the frequency is steadily increased, phase variability increases and there is a tendency to transition from 180° to 0°; Kelso, 1984). These are typically the only two coordinations people can produce stably without practice; other relative phases are easily perturbed by small errors leading to a transition to one of the stable states. This basic pattern was captured in the original Haken-Kelso-Bunz (HKB) model (Haken et al., 1985), which describes 0° and 180° as the only attractors in a potential function spanning the space of possible relative phases (see Golonka & Wilson, 2012 and Kelso, 1995 for overviews, and Park & Turvey, 2008 for a detailed analysis of the nature of the HKB modelling approach).

In human movement coordination, relative phase can be defined in two different frames of reference: an egocentric, body relative frame of reference; and an allocentric, external frame of reference.

### 2.1. The egocentric frame of reference

The egocentric frame of reference is body centred about the sagittal midline. In this frame, a coordinated rhythmic movement that entails mirror symmetrical movements (i.e. in-out/in-out movements) about the midline is referred to as *in-phase* coordination. Side-to-side movements (e.g. in-out/out-in) are referred to as *anti-phase* coordination. In-phase movements are more stable than anti-phase movements. The HKB model (Haken et al., 1985) defines relative phase in an egocentric frame of reference.

This *egocentric constraint* (Swinnen, 2002) on coordination stability is attributed to muscle homology. Homologous muscles are the functionally equivalent muscles in matching limbs; for example, the biceps of the two arms are homologous, as are the triceps. Thus, under normal postural conditions, in-phase coordinations require the simultaneous use of homologous muscles, and anti-phase coordinations require the simultaneous use of non-homologous muscles.

One proposed mechanism for how muscle homology might affect coordination stability is neural crosstalk (e.g. Marteniuk, MacKenzie, & Baba, 1984; Swinnen, Young, Walter, & Serrien, 1991). Specifically, when non-homologous muscles must be activated simultaneously, the relevant motor commands interact with and inhibit one another at various stages of planning and implementing the movement. This has been formalised in several models (e.g. Beek et al., 2002; Cattaert et al., 1999; Daffertshofer et al., 2005).

### 2.2. The allocentric frame of reference

Coordinated rhythmic movements must be parallel to each other to produce the HKB stability differences, because relative phase is only uniquely defined under these conditions. When two coordinated movements are orthogonal to each other, the asymmetries between in-out/in-out motions and in-in/out-out motions disappear (e.g. Bogaerts, Buekers, Zaal, & Swinnen, 2003; Wimmers, Beek, & van Wieringen, 1992).

This means that there is a second human-relevant way to define relative phase, and that is in an allocentric frame of reference. In this frame, when the two oscillators in a coordinated rhythmic movement move in the same direction throughout the cycle, they are at *0*° mean relative phase. When they move in the opposite direction throughout the cycle, they are at *180*° mean relative phase. 0° movements are more stable than 180° movements. The Bingham model (Bingham, 2001, 2004, 2004b; Snapp-Childs et al., 2011) defines relative phase in an allocentric frame of reference.

This *allocentric constraint* (Swinnen, 2002) on coordination stability is attributed to the relative direction of motion of the two oscillators. 0° coordinations are more stable than 180° because relative direction is more stable (and because the relative speeds are lower; Snapp-Childs et al., 2011). Intermediate relative phases are specified by varying proportions of the same/different direction of motion and cannot be stably produced without training.

There are two strands of research that have revealed the effects of the allocentric constraint on coordination stability. The first strand investigated coordination of non-homologous limbs (e.g. Serrien & Swinnen, 1997; Swinnen, Dounskaia, Verschueren, Serrien, & Daelman, 1990). In these tasks, muscle homology is not definable and coordination stability was strongly governed by the relative direction of motion (with isodirectional, 0° coordination more stable than non-isodirectional, 180° coordination).

The second strand considers the perception of relative phase. The first clue that internal, neural constraints may not be the sole player came from Schmidt, Carello, and Turvey (1990), who showed that the HKB stability pattern persisted when two people coordinated with each other, coupled only by vision. Bingham then embarked on a research program to investigate the informational basis for the perception of relative phase. He and colleagues have shown the HKB pattern in judgments of relative phase and phase variability, both visually (Bingham, 2004b; Bingham, Schmidt, & Zaal, 1999; Bingham, Zaal, Shull, & Collins, 2001; Zaal, Bingham, & Schmidt, 2000) and haptically (Wilson, Bingham, & Craig, 2003). Unstable coordinated actions (such as 90°) can also be stably produced without training if the visual feedback is altered to be more readily detected. This can be done by mapping a non-isodirectional coordination movement into an isodirectional feedback display (Wilson, Collins, & Bingham, 2005a), or by removing the relative direction component entirely with Lissajous feedback (Kovacs, Buchanan, & Shea, 2009a, 2009b; Kovacs & Shea, 2011). Perceptual stability leads to action stability, independently of how the limbs are being used.

This research has been formalised into a perception-action model of coordinated rhythmic movement (Bingham, 2001; Bingham, 2004a, 2004b; Snapp-Childs et al., 2011; see Golonka & Wilson, 2012 for an overview). This model couples two phase-driven damped mass-spring oscillators via perceived relative phase. The information for relative phase is the relative direction of motion, with the