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Q1 # Coordination Dynamics

Q2 Gregor Schöner* and Eva Nowak
Institut fuer Neuroinformatik, Ruhr-Universität Bochum, Bochum, NRW, Germany

Synonyms

Haken-Kelso-Bunz model

Definition

Voluntary movements are typically coordinated in the sense that their components form ordered patterns. This includes the coordination of different spatial components of a movement, the coordination of different limbs, and also the coordination of movement with perceived events. More formally, coordination is characterized by stable relative timing of the movement components. Coordination dynamics is a theoretical approach to understanding how coordination arises which postulates that neural oscillators control the timing of each component. The coupling among such neural oscillators leads to stable relative timing. Mathematical models of coordination dynamics have been formulated at the level of the neural oscillators and their coupling, but also at the level of relative phase itself as a macroscopic, phenomenological variable. The observation of instabilities in relative timing has provided support to the notion of coordination dynamics.

Detailed Description

Coordination

That the different limbs are coordinated during locomotion seems obvious, although the phenomenon of relative coordination, in which one limb makes an extra cycle every now and then, shows that coordination requires a quantitative approach (Holst 1973). Rhythmic movements like dancing and making music, but also movements like chewing and speaking that are approximately rhythmic, are coordinated in the sense that the relative timing of movement components remains invariant in time and, within limits, across changes of movement parameters such as speed and amplitude (Schöner 2002). Direct evidence for stable relative timing is obtained when a coordination pattern recovers from a perturbation, the lagging component catching up and the leading component falling back to reinstate the pre-perturbation pattern (Schöner and Kelso 1988). Discrete motor acts are also coordinated in the sense that their durations are aligned when the movements are performed concurrently, but not when they are performed separately (Kelso et al. 1979). The coordination of movements with external events, for example, intercepting a moving object may show the same characteristics of relative timing (Warren 2006).

To assess the convergence of coordination patterns that defines their stability, a distance measure among patterns of coordination is needed. The relative phase is such a measure. It is defined as the

*Email: gregor.schoener@neuroinformatik.ruhr-uni-bochum.de
*Email: gregor.schoener@ini.ruhr-uni-bochum.de

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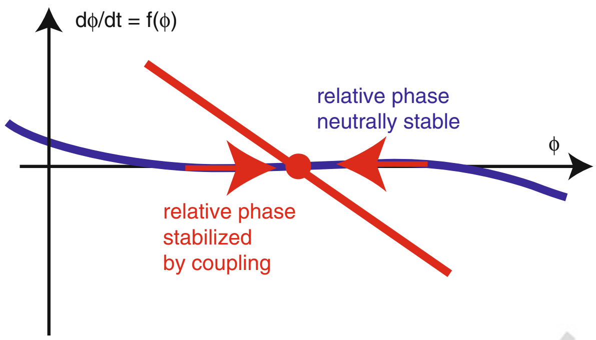

Fig. 1 The rate of change of relative phase, $d\phi/dt$, plotted against relative phase, ϕ, has a set of marginally stable fixed points when the underlying oscillators are weakly coupled (*blue solid line*) that coalesces into a single-stable fixed point for sufficiently strong coupling (*red solid line*). The *red arrows* illustrate how the negative slope of the relative phase dynamics leads to convergence to the fixed point which accounts for recovery from perturbations and resistance to noise. The loss of stability for weak coupling leads to predictions of increased variance and relaxation time (Schöner et al. 1986)

temporal offset of matching events in two timed movements, measured in percent of the movement time (Schöner 2002).

Neural Oscillators

A key theoretical idea for understanding coordination is that the timing of voluntary motor acts is generated from neural oscillators, whose stable limit cycles drive the effector systems (Schöner 2002). This idea is not limited to rhythmic movement. For discrete motor acts, the limit cycle may be instantiated via a bifurcation at the beginning of the movement and terminated by another bifurcation at the end of a single cycle (Schöner 1990). Perceived events may drive these bifurcations, accounting for the timing of discrete motor acts relative to the environment (Schöner 1994).

Coordination is brought about by coupling multiple such oscillators. Coupling generically induces phase locking (see entry on Multistability of Coupled Neural Oscillators). This can be visualized by looking at the rate of change of relative phase as a function of relative phase (Fig. 1). Limit cycle oscillators always have one Lyapunov exponent that is zero, which reflects that there is no resistance to perturbations that shift the oscillator along the limit cycle. In uncoupled oscillators, the dynamics of the relative phase has a line of fixed points that are marginally stable. Coupling most strongly affects the direction in phase space, in which the vector field is zero, leading generically to a stable fixed-point attractor for relative phase that represents a stable pattern of coordination.

Link to Experiment

The dynamics of relative phase has been used as a direct phenomenological model of the dynamics of coordination (Schöner et al. 1986). In particular, experimental evidence for loss of stability, observed through enhanced fluctuations and slowed relaxation after perturbations, has highlighted that stability is a necessary concept for an understanding of coordination. Loss of stability is typically observed for antiphase patterns of coordination (homologous limbs alternate) when movements become faster (Schöner and Kelso 1988).

The coupled neural oscillators themselves have also been used as a level of description of coordination patterns (Haken et al. 1985; Grossberg et al. 1997) to account for the role of movement amplitude. Behavioral data suggest that what determines the stability of the coordination pattern may be the spatial arrangement of movement components, not necessarily the anatomical nature of the components (Mechsner et al. 2001). If this were true, then perhaps cortical oscillators that control

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movement in space, rather than spinal oscillators directly linked to the effectors, would be the basis for coordination.

Cross-References

Q3

- ▶ Bifurcations, Neural Population Models and
- ▶ Embodied Cognition, Dynamic Field Theory of
- ▶ Multistability in Motor Control
- ▶ Multistability of Coupled Neural Oscillators

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Further Reading

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