Stability and Variability of Rhythmic Coordination with Compromised Haptic Perceptual Systems

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The synchronizing of rhythmically moving limbs and limb segments is one of the most fundamental achievements of the human movement system. It attracts considerable scientific attention because it is a primary expression of how movements are organized in space and time, how they resolve issues of efficiency, and how they meet the competing challenges of stability and flexibility. More broadly, 1:1 frequency locking can be viewed as one of human movement’s original models for a collective form of organization in which many component parts, distributed across the body, act coherently to produce a global action.

A complex system’s collective dynamics are relatively independent of the specific details of the internal and external interactions of its component subsystems. Accordingly, the collective dynamics—for example, of synchronized rhythmic hand movements—can be usefully modeled in relative ignorance of the constituent dynamics. As developed by Kelso (1995) and colleagues, the elementary rhythmic 1:1 synergy can be modeled by a motion equation in the collective variable of relative phase $\phi$—the difference in the phase angles ($\theta_{\text{left}} - \theta_{\text{right}}$) of the left and right limbs. Thus,

$$\dot{\phi} = \Delta \omega - a \sin(\phi) - 2b \sin(2\phi) + \sqrt{Q} \zeta_t.$$  

(1)

The overdot signifies the first time derivative, $\Delta \omega$ is a detuning term that can be equated with the difference $(\omega_{\text{left}} - \omega_{\text{right}})$ between the uncoupled frequencies of the limbs, and $a$ and $b$ are coefficients that determine the relative strengths of attractors for the coordination at or in the vicinity of the values $\phi = 0$ and $\phi = \pi$. The faster interactions among the internal subsystems are identified with $\zeta_t$, a Gaussian white noise process of strength $Q > 0$. The predictive successes of the state dynamics expressed through Eq. 1 (summarized in Amazeen, Amazeen, & Turvey, 1998) indicate the intimate connection between motor timing and stability and the significance of symmetry breaking ($\Delta \omega \neq 0$).
Fig. 1a shows a method for investigating the predictions of Eq. 1. Pendulums held in the two hands can be of varied lengths and masses, thereby manipulating their preferred frequencies. In this example, movement speed is freely chosen. If the pendulums are the same, $\Delta \omega = 0$. Among the basic facts of bimanual rhythmic coordination are: (a) increased deviation from required relative phase when $\Delta \omega \neq 0$; (b) greater change in stable relative phase per change in $\Delta \omega$ for intended antiphase than intended inphase coordination (Fig. 1b); and (c) increased variability in relative phase (SD $\phi$) when $\Delta \omega \neq 0$ (Fig 1c).

Rhythmic coordination in older adults

Establishing spatio-temporal relations among body segments is made possible by information about the states of muscles, limb segments, and limb attachments. This information is realized in the patterned activity of mechanoreceptors in response to distortions of the body’s tissues due to movement and environmental contacts. Mechanoreceptors decline with age and certain illnesses, however, leaving individuals with reduced awareness of their bodies and of the surfaces and objects they are in contact with. This neuropathy results in the loss or partial loss of sensitivity in touch and the muscle sense, with unknown consequences for everyday functionality (manipulating objects, using tools, walking). For example, it may have consequences for the on-line tuning of muscular synergies that enables coordinated manual behaviors.

How similar are the collective dynamics of interlimb coordination across age levels? We have compared 4 younger (mean 25 years) and 4 older (mean 68 years) adults in the task shown in Fig. 1a. In an experiment with inphase and antiphase coordination and three values of $\Delta \omega$ (0, ±2 rad/s), ANOVA found no age effects on relative phase or its fluctuations in either coordination mode and no interactions of age with $\Delta \omega$ (Fig. 2). Within the limits of the experiment, it would seem that both groups abide by Eq. 1. Variability of performance measures are reported to be greater in the elderly (e.g., Darling, Cooke, & Brown, 1989). The results shown in Fig. 2 suggest that the opposite may be true when one is considering the moment-to-moment variability of a rhythmic coordination. Despite age-related decrements in sensory structures, older adults showed
no apparent deterioration in rhythmic coordination of homologous limbs at a self-selected pace. It remains to be seen whether interlimb behavior of individuals with reduced proprioceptive information may be affected when the coupling between limbs is weakened—in tasks that require, for example, movement at faster speeds or coordination of nonhomologous limbs.

**Rhythmic coordination and peripheral neuropathy**

A more dramatic loss of sensitivity accompanies the clinical condition *peripheral neuropathy*, a functional deafferentation that accompanies certain diseases or injury. Individuals with neuropathy cannot feel anything touching the affected limb, nor can they feel the limb itself (its location, orientation, or extent). Given that proprioceptive information may be particularly important for maintaining the co-ordination of the limbs during bimanual movements, peripheral neuropathy presents an interesting test of Eq. 1.

The patient CA was diagnosed with peripheral neuropathy in the left arm, extending from the hand through the elbow with some involvement of the shoulder. The condition was due to a growth on the sensory tract at the top of the spine that appeared at 40 years of age. The lack of sensation in the left arm was confirmed by an identification task in which a succession of plastic numbers (approximately 2 cm × 2 cm × 1 cm deep) were placed in her hand. Without being able to see the numbers, she correctly identified all using the unaffected (right) hand. With her left hand, however, she could identify none of the numbers correctly (and, indeed, dropped them because she could not feel that they were in her hand).

The pendulum task was used again: Inphase and antiphase coordination performed without vision, freely chosen movement speed, and five values of $\Delta \omega$ (0, ±1 rad/s, ±2 rad/s). Fig. 3 shows the pattern of results as a function of intended phase and $\Delta \omega$. But note how large the phase deviation is compared to the elderly participants (Fig. 2a vs. Fig. 3a). $SD_\phi$, in contrast, is not unusual (Fig. 2b vs. Fig. 3b). A phase deviation of 30˚ typically is seen only under especially challenging conditions (e.g., speeded coordination with concomitant cognitive
activity; Pellecchia & Turvey, 2001). The observed phase deviation may reflect an attentional asymmetry. Attention directed to the left limb leads to a coordination dynamic that is more left leading (Amazeen et al., 1997). Given the loss of proprioceptive information about the left arm, CA may well have directed attention to that side (e.g., so as not to drop the pendulum). Of note, SDφ was lowest for zero detuning, suggesting this was still the most stable condition, despite a phase shift greater than that demonstrated for the negative detuning conditions.

Conclusion

The human ability to synchronize the movements of two limbs is fundamental. It has been argued that the coupling between limbs is informational (rather than neural). Just as the contribution of cognitive activity plays out in the fundamental coordination equation so, too, does the damping of information that accompanies neuropathy. Nonetheless, the field-like structure of the mechanoreceptor support for haptic perception allows the basic features of bimanual coordination to be preserved.

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References


