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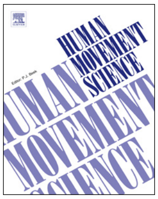

Full Length Article

Joint dyadic action: Error correction by two persons works better than by one alone

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ABSTRACT

We investigated how two people learn to coordinate their movement to achieve a joint goal. Pairs of participants oscillated a joystick with their dominant hand whilst looking at a common feedback, a Lissajous figure, where each participant controlled either the vertical or horizontal coordinate of a moving dot. In the absence of specific instructions, inter-personal coordination was highly variable, punctuated by intermittent phase locking. When participants were required to produce a circular Lissajous figure, coordination variability decreased while accuracy, transfer entropy and the incidence of stable coordinative solutions (fixed points, including bi-stability) increased as a function of practice trials. When one partner closed his/her eyes, so that the other one received the full control of error correction, the stability and accuracy of coordination decreased. A questionnaire showed that partners experienced the feeling of we-control. The results were interpreted in terms of a disturbance ~ correction challenge: joint action is enhanced by having a flexibly adjusting co-actor rather than a more predictable, but not adjusting, partner. At transfer, partners were able to produce a new, never-practiced Lissajous pattern, evidencing the generalisability of joint learning.

1. Introduction

Typically, learning is understood and studied as a process taking place uniquely within the confines of a single person. Yet, learning may often develop inside a broader learning unit, such as sport teams, work groups, military troops, or the family circle. These collectives may exhibit coherent and purposeful patterns of inter-individual behaviors in which each individual's behavior may be meaningless for each member functioning alone, for instance while making a death spiral in pair skating, creating a defensive alignment in football, or performing a surgical operation. Many human endeavors involve social coordination (Moll & Tomasello, 2007; Vygotsky, 1978), and so do their acquisition and/or improvement.

Despite recent renewal of interest in social processes, few studies have scrutinized the mechanisms of perceptual-motor learning in social units. Some have focused on learning by observation, where an immobile learner benefits from observing someone else performing a motor skill (Andrieux & Proteau, 2014; Carroll & Bandura, 1985; Granados & Wulf, 2007; Hodges, Williams, Hayes, & Breslin, 2007; Karlinsky & Hodges, 2017; Pollock & Lee, 1992). Collective learning situations, where all partners contribute, symmetrically or not, to co-produce a shared motor outcome (Pacherie, 2011; Searle, 2002), such as dancing, rowing, or pushing a heavy

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object together, have only given rise to few empirical studies (e.g., Knoblich & Jordan, 2003; Kostrubiec, Dumas, Zanone, & Kelso, 2015; Richardson et al., 2015). In the present paper, we utilize conceptual tools and coordination measures stemming from Coordination Dynamics (Kelso, 1995; Huys, Studenka, Rheaume, Zelaznik, & Jirsa, 2008) to investigate how two partners learn to coordinate the timing of their movements when aiming to co-produce a shared perceptual-motor outcome.

1.1. *Inter-individual coordination dynamics*

We basically employed a version of the joint action paradigm addressing inter-personal coordination, which we adapted to the study of inter-personal coordination learning. In the classic inter-personal coordination task as employed by Amazeen, Schmidt, and Turvey (1995); see also Schmidt, Carello, and Turvey (1990), Tognoli, Lagarde, DeGuzman, and Kelso (2007), Richardson, Marsh, and Schmidt (2005), the two partners of a dyad are asked to continuously oscillate a limb while watching the other's limb movements. In such cases, the individuals typically show a spontaneous tendency to synchronize their oscillating body parts. The tendency is deemed spontaneous because it arises 'on its own', without explicit intention, instruction, and learning. Similarly, in ecological situations, people spontaneously tend to rock, walk, or clap in unison (Fitzpatrick, Schmidt, & Carello, 1996; McNeill, 1995; Neda, Ravasz, Brechet, Vicsek, & Barabasi, 2000; Schmidt, Carello, & Turvey, 1990; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Varlet, Marin, Lagarde, & Bardy, 2011; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008). These findings suggest that inter-personal coordination is a naturally arising and universal phenomenon. In fact, humans are hardly able to ignore a partner's motion even if asked to do so (Atmaca, Sebanz, & Knoblich, 2011; Sebanz, Bekkering, & Knoblich, 2006).

In the parlance of Coordination Dynamics (Kelso, 1995; Kelso, Dumas, & Tognoli, 2013), the spontaneous tendency to move in unison or in alternation is ascribed to the existence of spontaneously stable coordination patterns: in-phase and anti-phase, respectively (Kelso, 1984). These patterns are said to be intrinsically stable as about everyone can perform them, up to a certain movement frequency, without prior training (Kelso, Scholz, & Schöner, 1986). In both patterns, two homologous limbs oscillate at the same frequency; in the in-phase pattern, the lag between the limbs is zero, whereas in the anti-phase pattern, it amounts to a half of a cycle. The key achievement of Coordination Dynamics lies in discovering how coordination and its properties are to be assessed. It has been proven that the inter-limb lag is reliably captured by relative phase (RP), amounting to 0° for in-phase and 180° for anti-phase. Pattern stability scales with, and is therefore typically measured by RP variability: the more stable the pattern, the less variable its RP (Schöner, Haken, & Kelso, 1986). These patterns have been mathematically formalized as stable solutions – more specifically, stable fixed points or attractors – of a generative function determining coordination: the relative phase dynamics (Haken, Kelso, & Bunz, 1985). When the relative phase's time derivative is plotted as a function of relative phase, the attractors are geometrically identified as the zero-crossing points for which the derivative displays a negative slope. As explained in the Method section, these stable attractors can be mathematically identified in experimental data by a switch in the sign of two successive Kramers-Moyal coefficients (Huys et al., 2008). Coordination relies on the exchange of information between involved components. The information flow coming from a partner to another can be assessed by transfer entropy (Schreiber, 2000), a measure stemming from the mathematical theory of information. Roughly speaking, transfer entropy quantifies the influence one partner has on the other by estimating how much the uncertainty in the future states of participant Y is reduced by knowing the past states of partner X (see Method for further details). Overall, the dynamics accounted for various coordination phenomena, whatever the nature of the coupling between components: the neural information exchanged between two limbs of a single person or the perceptual information between the limbs of two distinct individuals (Schmidt et al., 1990; see Kelso, 1994, and Kelso, 1995 for a review).

1.2. *Coordination learning with a Lissajous figure*

Performing relative phase patterns other than 0° and 180°, or producing frequency relations other than 1:1 between the limbs, typically requires some practice with the help of feedback displaying the RP to be learned (e.g., Temprado & Swinnen, 2005; Wenderoth, Bock, & Krohn, 2002; Zanone, Kostrubiec, Albaret, & Temprado, 2010). In individual learning studies, it has been shown that performance improvement can be enhanced when the information about the required RP is shown in a Lissajous figure (Hurley & Lee, 2006; Kovacs & Shea, 2011; Swinnen, Lee, Verschueren, Serrien, & Bogaerds, 1997). A Lissajous figure is a visual representation blending the information coming from two limbs into a single dot displayed on a computer screen since the angular position of each limb is used as the coordinates of the abscissa and the ordinate of the dot at each instant. The Lissajous figure resulting from the displacement of the dot depends on the difference between the limbs amplitudes, frequencies and phases (Maor, 2013). When the amplitudes and frequencies of both actors' oscillations are equal, and one limb lags the other by a quarter of a cycle (i.e., 90° RP), the resulting dot motion traces a circle (Fig. 1, top left panel). If the lag gradually decreases to zero, the circle transforms into an ellipse and then to a right-slanted slope at 0° RP (Fig. 1, top row panels). For equal amplitudes, constant lag but distinct frequencies, more complex shapes emerge, including self-intersecting open or closed curves (Fig. 1, middle and bottom row panels). If the frequencies ratio is irrational, the dot never retraces its own path, giving rise to dense and complicated curves (Fig. 1, bottom row, right panel) (Maor, 2013).

1.3. *Our experimental task*

To date, Lissajous figures have been widely used as augmented feedback for helping the learning of individual bimanual coordination, in which a person is asked to oscillate two homologous limbs in order to produce a visually simple Lissajous figure (Hurley & Lee, 2006; Kovacs, Buchanan, & Shea, 2010a; Kovacs, Buchanan, & Shea, 2010b; Kovacs, Buchanan, & Shea, 2009; Lee,