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Viviane Kostrubiec, Raoul Huys, Pier-Gorgio Zanone. Joint dyadic action: Error correction by two persons works better than by one alone. *Human Movement Science*, 2018, 61, pp.1-18. <10.1016/j.humov.2018.06.014>. <hal-04139753>

**HAL Id: hal-04139753**

**<https://hal.science/hal-04139753v1>**

Submitted on 10 Jul 2024

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**Cite this article:** Kostrubiec, V., Huys, R., & Zanone, P.-G. (2018). Joint dyadic action: Error correction by two persons works better than by one alone. *Human Movement Science*, 61, 1-18.  
<https://doi.org/10.1016/j.humov.2018.06.014>

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

Viviane Kostrubiec<sup>a,b,\*</sup>, Raoul Huys<sup>c</sup>, Pier-Gorgio Zanone<sup>c</sup>

<sup>a</sup> Centre d'Etudes et de Recherches en Psychopathologie et Psychologie de la Santé, Université de Toulouse, UT2J, Maison de la Recherche, Allée Antonio Machado, 31058 Toulouse Cedex 9, France

<sup>b</sup> Université de Toulouse, UPS, 118, route de Narbonne, 118, route de Narbonne, 31062 Toulouse Cedex 9, France

<sup>c</sup> Centre de Recherche Cerveau & Cognition, Université de Toulouse, UPS, Pavillon Baudot, CHU Purpan, Place du Dr Baylac, 31059 Toulouse, France

**Corresponding author:** V. Kostrubiec, Centre d'Etudes et de Recherches en Psychopathologie et Psychologie de la Santé, Université de Toulouse, UT2J, Maison de la Recherche, Allée Antonio Machado, 31058 Toulouse Cedex 9, France, [viviane.kostrubiec@univ-tlse3.fr](mailto:viviane.kostrubiec@univ-tlse3.fr)

## 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.

**Keywords :** Social learning, Joint action, Distributed control, Coordination, We-control, Lissajous figure

## 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

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  $0^\circ$  for in-phase and  $180^\circ$  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  $0^\circ$  and  $180^\circ$ , 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.,  $90^\circ$  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  $0^\circ$  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,

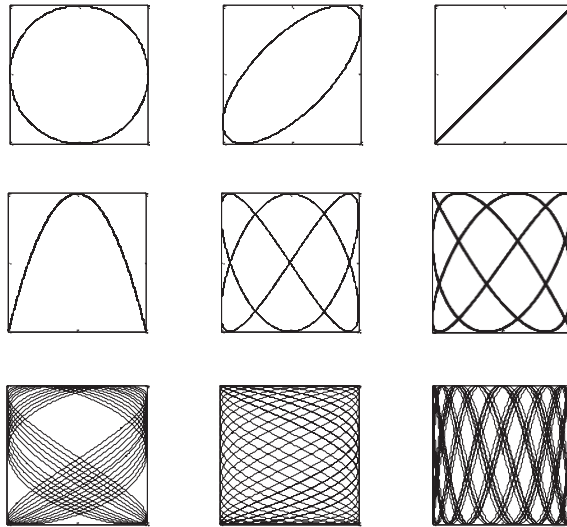


Fig. 1. Lissajous figures. Computer-generated Lissajous figures, produced by two sines ( $\sin x$ ) governing the coordinates of the abscissa and the ordinate of the dot motion, with equal amplitude but various frequency ratios (FR) and relative phases (RP). Top row: FR = 1, RP of  $90^\circ$ ,  $45^\circ$  and  $0^\circ$  (from left to right); Middle row: FR = 2:1, RP =  $90^\circ$  (left); FR = 3:2, RP =  $0^\circ$  (middle); FR = 7:5, RP =  $0^\circ$  (right); Bottom row: FR = 1:1.49, RP =  $90^\circ$  (left), FR = 1:1.9, RP =  $36^\circ$  (middle), FR =  $\sqrt{13}$ :1, RP =  $0^\circ$  (left).

Swinnen, & Verschueren, 1995; Smethurst & Carson, 2001; Wilson, Snapp-Childs, Coats, & Bingham, 2010; Zanone & Kelso, 1992). Here, we used the Lissajous figure as feedback in the learning of a joint action between two persons: In the following experiments, pairs of participants were asked to co-produce a circular Lissajous figure ( $\pm 90^\circ$  RP) by oscillating a joystick with their dominant hand. The movement of one participant was mapped onto the horizontal motion of the dot, while the other participant's movement was mapped onto its vertical motion. Participants were not informed about the mapping rule. In contrast to the bimanual and interpersonal coordination task used to date, participants were also forbidden to look each other's moving limbs. As such, participants were prohibited from perceiving inter-limb relative frequency, relative speed, relative position or relative direction, which are the variables conveying the information allowing the arising of intrinsically stable patterns (Wilson, & Bingham, 2008). Therefore, no spontaneously stable patterns were expected to exist in the present study.

#### 1.4. Disturbance ~ correction challenge in distributed control learning

When the control of Lissajous feedback is distributed over two persons, the task poses an interesting challenge: How does a dyad come to learn a shared motor outcome, say, a circular Lissajous figure that continuously depends on the movement of both partners for it to be achieved? In the individual learning situation, the learner accomplishes a task that is fully under his/her control. Following established learning theories (Körding & Wolpert, 2004; Schmidt, 1975), error correction may proceed by comparing the anticipated efferences to those actually produced, and by adjusting the ongoing motor command accordingly. Anticipation and adjustment may well be effective for learning in contexts and environments that evolve predictably. In joint action, however, where several individuals are contributing parts of a broader learning system, this error correction mechanism is no longer feasible, since the effect of a corrective movement undertaken by one partner depends on what the other partner is doing simultaneously. Whether a partner's movement is corrective or disruptive for the joint output depends on the simultaneous and beforehand unknown action of the other, raising a disturbance ~ correction challenge, to use the formalism introduced by Kelso and Engström (2006), where the tilde symbol ( $\sim$ ) refers to a complementary pair of united antagonist effects. If verbal communication, stops, and turn-taking are prohibited, each learner faces not just a hard-to-predict or hard-to-accommodate environment but an *a priori* unpredictable hence unknown environment. The question thus arises of how two individuals come to learn to produce a given Lissajous figure in unison. Of course, a mere error correction mechanism could work if one partner of a dyad was to abandon all pretense to error correction and produced an oscillation at a constant, hence soon predictable frequency, thus leaving all the actual control to the partner. For this reason, in the present work, we tested if such effect had happened using a questionnaire.

#### 1.5. Experimental rationale, paradigm and hypotheses

Learning success or failure is imputable to the overpowering reaction of the intrinsic dynamics toward the learning requirement (Kostrubiec, Zanone, Fuchs, & Kelso, 2012). Under such an umbrella, to investigate how two partners of a dyad learn to stabilise coordination with Lissajous feedback, one must find what the intrinsic dynamics are in the experimental setting. During practice, it is thus mandatory to use instructions sparsely in order to leave as much room possible to the expression of the intrinsic dynamics. A pretest-practice-transfer experimental paradigm was used here. At pretest, in which no practice goal was provided, partners were

merely asked to produce oscillations whilst watching the concurrent feedback offered by a Lissajous figure. Immediately after the spontaneous trials, the partners were involved in practice trials in which they were instructed to produce a circular figure on the screen. Learning a specific pattern is of little use both for learner and scientist more important is to know if learners developed a generalizable skill. To verify if any generalization was present, a brief transfer test was administered after  $\pm 90^\circ$  RP practice where participants tried to produce a never practiced RP ( $0^\circ$  or  $180^\circ$ ).

Coordination was assessed by three features: RP accuracy and stability, the presence of attractors, and the amount of information exchanged between partners. We expected that in the first five spontaneous (i.e., no goal) trials the participants would engage in an exploration phase, characterized by a substantial initial mismatch of individual frequencies and most variable shapes (Hypothesis 1). However, because individual limb variability is limited and couplings are known to be established spontaneously, we assumed the exploration to be incidentally punctuated by transient locking, expressing the rising of "ghost attractors". Ghost attractors can be operationally differentiated from stable fixed points by examining the Kramers-Moyal coefficients (Hypothesis 2).

At  $90^\circ$  practice, when instructed to produce a circular figure, we expected various markers of learning to appear: The individual frequencies of oscillation should converge toward one another, RP stability and accuracy should increase, and the incidence of attractors should rise (Hypothesis 3). The improvement may be attributed to the increase of the amount of information gathered from the partner's motion: transfer entropy should increase with learning (Hypothesis 4). After practice, we expect dyads to provide testimony of generalization: They should readily co-produce the never practiced diagonal Lissajous figure, corresponding either to  $0^\circ$  (right-slanted) or to  $180^\circ$  (left-slanted) RP. RP stability at transfer should be lower than the stability at practice but higher than the stability at the spontaneous test (Hypothesis 5). With regard to the individual behaviors, if ever each partner learned to perceive the difference between the changes occurring in his/her own limb and in the Lissajous figure, this may lead him/her to find out which coordinate of the dot movement was under his/her control and thus how his/her action complemented that of the partner (Hypothesis 6). After the experimental session, participants were asked about this issue and a questionnaire assessing their feeling of control was administered.

## 2. Experiment 1

### 2.1. Method

#### 2.1.1. Participants

Fifteen pairs of unpaid volunteers, all males, aged about  $23(\pm 5)$  years, self-claimed right-handed, took part in the study. All participants were undergraduate students at the Faculty of Sport Sciences in Toulouse, France. They were naive to the purpose of the study, reported normal or corrected-to normal visual acuity and had no physical impairment impeding their producing the required pattern. The study was approved by the local ethical committee of the Paul Sabatier University, and participants provided a written informed consent in accordance with the Helsinki Declaration.

#### 2.1.2. Material and apparatus

Participants were seated side by side in a dark room, separated by a barrier preventing them to see each other (Fig. 2). A 15" monitor was located in front of them, 70 cm away, on a table. Using their dominant hand, each participant grasped one joystick. Each joystick was fixed on the table and hidden inside a carton box. Each joystick allowed movements in the left-right direction with a maximal amplitude of  $\pm 40$  cm. Each joystick was connected to a linear potentiometer whose output was continuously sampled at 200 Hz, used to produce visual feedback through a Lissajous figure on the screen in real time, and stored in a PC for further treatment.

The Lissajous figure was provided in the form of a sequence of 15 green dots connected by a green line and moving on a black screen. The dot coordinates (x,y) were controlled by the instantaneous positions of the joysticks. The motion of the left joystick moved the dots up (extension) and down (flexion), whereas the motion of the right joystick moved the dots leftwards (extension) and rightwards (flexion). The dots displayed the current and 14 previous positions of the joysticks in real time thereby producing a trace.

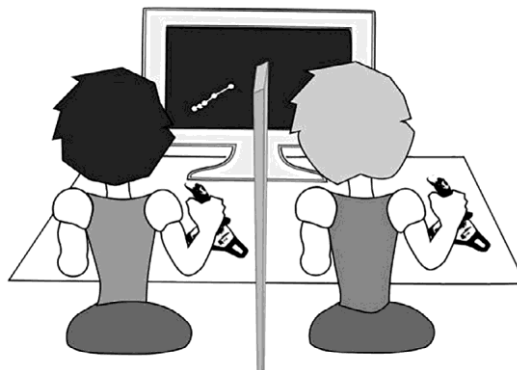


Fig. 2. Experimental setting (see text for details).

The entire real-time processes were controlled through a custom C program.

A questionnaire assessed how participants had experienced the control of drawing the Lissajous figure. The feeling of control, or of agency, refers to the subjective experience of being in control of the action outcome. We-agency, or we-control, arises when the control is ascribed to the team as a whole (Pacherie, 2014). To investigate whether RP stabilization is accompanied by the development of we-control, a test of control was inserted among 90° practice trials. During each test, participants made an explicit judgment about who was in control of the task: he/her, his/her partner or both (Pacherie, 2012). Three questions were asked to each partner: How much do you feel that you/your partner/both of you are in control of the Lissajous figure? For each question, participants provided a 100-level rating scale, introduced by van der Wel, Sebanz, and Knoblich (2012): They should select a level among the 100 levels ranging from 0 (no control at all) to 100 (complete control) by steps of one. Each question was displayed on a separate paper sheet, so that participants could see neither their ratings on the previous trials nor those provided by their partner.

### 2.1.3. Procedure

A ‘spontaneous-90° practice-0°/180° transfer’ procedure was adopted. To leave as much room as possible to spontaneous processes, participants were merely asked to look at the screen and oscillate the joystick left-right without stopping with their dominant hand, thus using the whole wrist-elbow-shoulder chain. The sense of rotation – clock-wise (90° RP) or anticlockwise (–90° RP) – was not prescribed and there was no metronome, that is, no required frequency. Verbal communication between participants during the experimental session was forbidden. The experiment began by five spontaneous trials, where participants should merely move the joystick whilst looking at the concurrent feedback displayed in the form of a Lissajous figure on the screen. Then the 90° practice began. Participants were instructed to attempt to trace circles on the screen. Five blocks (B1 to B5) of ten practice trials were administered. Each block was followed by a pause, during which each participant filled in the control questionnaire. Then, five transfer trials were provided, where participants should trace diagonals, corresponding to a RP of 0° (right-sloped diagonal) or 180° (left-sloped diagonal). Any diagonal, whatever its slope, was accepted. Each trial lasted 30 s, and the whole experiment took about 50 min. After the experimental session, participants were interviewed (“Who was in charge of the task; themselves, their partner or both”; “Who controlled the vertical and who the horizontal coordinate”).

### 2.1.4. Data reduction and analysis

Time series for  $x$  and  $y$  were typically oscillatory. The data were mean-centered, detrended and low-pass filtered using a second order dual-pass Butterworth with a cutoff frequency of 20 Hz. After this preprocessing, the continuous relative phase (RP) between both partners was computed using the Hilbert transform (Rosenblum & Kurths, 1998). For each trial, six dependent variables (see Table 1) were computed in order to characterize the produced pattern and the inter-individual exchange of information. For each block of practice, an index of the sense of control was collected from each participant. Then, statistical analysis was undertaken in order to test whether dyads learned to coordinate over time and whether any possible coordination was accompanied by a rise in the amount of information gathered from the partner.

**2.1.4.1. Coordination measures: frequency ratio, accuracy, and stability.** In order to calculate the deviation from a 1-to-1 frequency-locking ratio, we computed the spectral densities for the position time series of both individuals of each dyad, and extracted the frequency in which the most power was contained. We then calculated the ratio between the two (main) frequencies, and determined its absolute difference from one (i.e., the larger this distance, the further the ratio from 1-to-1), coined here as Frequency Ratio Distance. Absolute Error, assessed as the absolute value of the distance between the produced and required RP, provided an index of accuracy. Given that the coordination dynamics were potentially bi-stable, two distinct indexes of stability were used. First, using circular statistics, we computed the RP uniformity (Batschelet, 1981), which varies between 0 and 1 (representing zero and maximal variability, respectively). The lower the RP uniformity, the more stable the pattern. Whereas the RP uniformity can evidence RP variability decrease, it cannot differentiate whether the system only lingers close to a stable state, displaying so-called ghost attractor, or whether a stable fixed point is actually present. Second, therefore, we determined whether a dyad’s movements adhered to a stable fixed point, potentially at 90°, by estimating the first Kramers-Moyal coefficient of the RP ( $\phi$ ), that is, its deterministic dynamics (Huys et al., 2008; van Mourik, Daffertshofer, & Beek, 2006). In that regard, in the presence of noise, a system’s evolution is described via conditional probability distributions:  $P(\phi', t + \tau | \phi, t)$  indicates the probability to find the system at  $\phi'$  (i.e., a state) at a time  $t + \tau$  given its previous state  $\phi$  at an earlier time  $t$ . Thus  $\phi$  refers to the RP at a time  $t$  and  $\phi'$  to the RP at a later time  $t + \tau$ . We computed these conditional probability distributions for each participant across blocks of five trials using a grid size of 8 relative phase bins (size =  $2\pi/8$ ). The first Kramers-Moyal (or drift) coefficient was computed as:

Table 1  
Dependent variables used in Experiment 1 to assess coordination, with their meaning.

Dependent variable	Meaning
Frequency ratio distance	Is there inter-individual frequency matching?
Absolute error of RP	Is coordination accurate?
RP uniformity	Is coordination stable?
FP incidence	Do coordination attractors rise?
Bistability incidence	Is coordination dynamics bi-stable?
Transfer entropy	What is the amount of information flowing from a partner to another?

$$D(\phi) = \lim_{\tau \rightarrow 0} \frac{1}{\tau} \int_{(\phi-\phi)}^{(\phi+\phi)} P(\phi', t + \tau | \phi, t) d\phi' \quad (1)$$

These coefficients numerically represent the vector field of the relative phase  $\phi$ . A fixed point is present whenever two successive coefficients switch sign, that is, whenever the line represented by these coefficients crosses the  $D = 0$  horizontal. The fixed point is stable when the slope of the line is negative and unstable when the slope is positive. If no fixed point exists, the relative phase  $\phi$  drifts. We estimated the degree of attraction (whenever a stable fixed point was identified) by calculating the slope of the (local) zero crossing defined across two subsequent bins. Only negative slopes, indicative of stable fixed points or attractors, were retained for further analysis. For the sake of simplicity, we focused on absolute values: the larger the slope, the more stable the fixed point. We next computed fixed-point incidence, as the frequency of occurrence of stable fixed points in each bloc. In addition, for each spontaneous, 90° practice, and 0°/180° transfer block, we calculated the number of trials in which the Kramers-Moyal coefficients indicated the existence of two stable fixed points to which we refer as the bistability incidence.

**2.1.4.2. Information measures: transfer entropy.** Transfer entropy (Schreiber, 2000) captures the amount and the direction of the information flow exchanged between two (oscillating) systems, X and Y. For X as source and Y as target, it assesses how much the uncertainty about the next state of Y is reduced—or how much predictability is gained—by knowing the past activity of X, in addition to what is already known about Y's past (Kleeman, 2011). To predict a next value of Y,  $y(i + \tau)$ , transfer entropy (TE) uses  $k$  previous samples of the variable Y, composing a Y past-states vector of length  $k$ , and  $m$  previous samples of variable X, composing a X past states vector of length  $m$ . Formally, TE from X to Y may be represented as a difference between two conditional entropies (Kleeman, 2011) (Eq. (2)):

$$T_{X \rightarrow Y} = H(Y_{i+\tau} | Y_i^{(k)}) - H(Y_{i+\tau} | Y_i^{(k)}, X_i^{(m)}) \quad (2)$$

where  $i$  indicates a given instant. TE entropy is null—or X and Y are independent—if the next state of Y depends solely on its  $k$  previous states but not on the  $m$  previous states of X, in other words, when information about the  $m$  previous states of X does not improve the prediction of the state of Y at a time  $i + \tau$ . TE is positive if including the information about past states of X improves the prediction of the next state of Y beyond the prediction based only on the past states of Y. The improvement in prediction is calculated in bits. To compute the transfer entropy we used a symbolization technique introduced by Martini et al. (2011), Staniek and Lehnertz (2008), which has proved to be a more robust and computationally faster technique than TE (Kugiumtzis, 2009). In line with Vicente's methodology (Korjus, 2011), the time lag parameter ( $\tau$ ) was chosen as the first zero-crossing of the autocorrelation function in each trial. Past states vectors were  $k = m = 5$  values long.

### 2.1.5. Statistical analysis

To assess whether and how participants learned the to-be coproduced RP, a 7 (Block = {spontaneous, B1, B2, B3, B4, B5, transfer}) ANOVA with repeated measures was carried out on all dependent variables. If appropriate, this analysis was complemented with orthogonal contrasts. Contrasts compared each level of Block to a fixed reference level. Performance in the spontaneous condition was selected in the first contrast as the reference level to test the efficiency of the 90° practice; 0°/180° transfer was assigned as reference level in the second contrast testing for performance deterioration at transfer. Polynomial contrasts were computed to look for linear trends indicative of increases/decreases. Next, we analysed the 90° practice blocks separately. A similar 5 (Practice Block = {B1, B2, B3, B4, B5}) ANOVA assessed evolution of performance with practice, followed by polynomial contrast testing for trends. Finally, a 3 (Questions)  $\times$  5 (Practice Block) ANOVA with repeated measures on all factors was carried out on the sense of control ratings. If appropriate, the analysis was followed by t-tests with Bonferroni correction. For all results, only significant effects at  $p < 0.05$  are reported along with corresponding estimates of effect size by partial eta squared ( $\eta^2$ ). When sphericity assumption was violated, Greenhouse-Geisser correction was used. The statistical analysis was performed using SPSS and R®.

## 2.2. Results

### 2.2.1. Visual inspection of the data

Fig. 3 displays data collected on an individual trial at mid-point of learning. The Lissajous figure starts to fill a form hesitating between a circle and a square (panel A) and the RPs to concentrate around  $-60^\circ$  (panel B). Positions begins to sustain a specific phase lag (panel C), as captured by the periods of nearly consistent discrepancy in phases (panel D) and the relative phase plateaux (panel E) framed by the two dotted lined boxes. These plateaux are separated by a period of RP drift, illustrated by the RP evolving between  $\pm 180^\circ$  RP. The whole trial is illustrative of a learning state where the learner fluctuates between short periods of stabilisation (singularised by dotted lined boxes in Fig. 3) and instability.

All RPs collected in the experiment, pooled over participants, are displayed in histograms in Fig. 4. At the spontaneous condition (panel A), the RPs histogram is close to flat, indicating that no preferred pattern exists; Following practice (panel B), it is bimodal, showing that the partners were successful in performing the required ( $\pm$ ) 90° RPs. At transfer (panel C), the RPs histogram displays a maximum close to 0°RP. The evolution of the RPs frequency distribution over the whole experiment (panel D) depicts a rise of a preferred RP at about  $-60^\circ$  at practice followed by the preferred RP shift toward 0° at transfer.

### 2.2.2. Coordination accuracy and stability

**Absolute error:** The Absolute Error (AE) as a function of Block is displayed in Fig. 5A. A 7 (Experimental Block) ANOVA on absolute

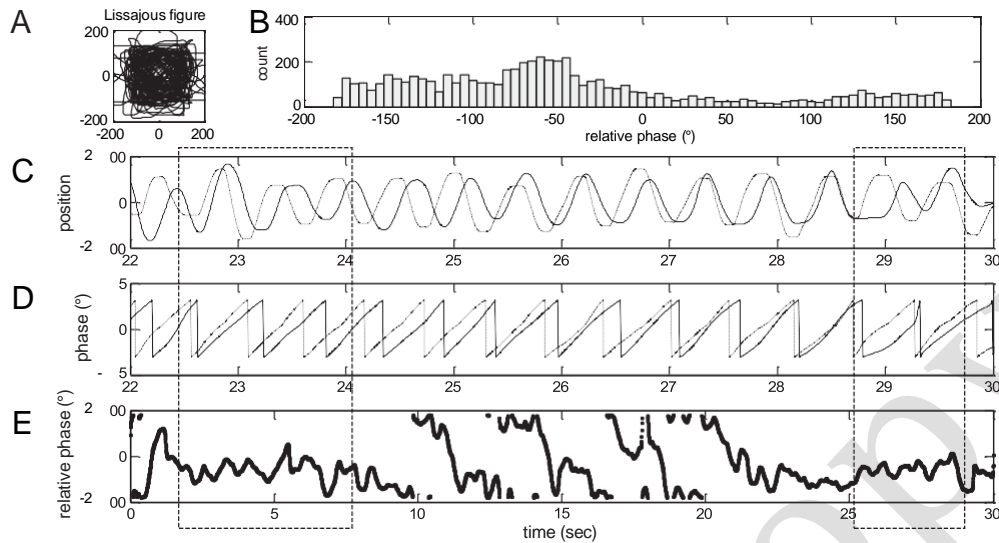


Fig. 3. Individual trial. Data collected in an individual trial: Lissajous figure (panel A), RP histogram (panel B), the evolution of positions (panel C), of corresponding phases in radians (panel D) and relative phases in degrees (panel E) as a function of time (s). The solid and dashed line in panels C–D display the data collected for partner 1 and 2, respectively. Dotted lined boxes frame two brief periods of RP stationarity, which may be seen as signs of ghost attractors (here at about  $-60^\circ$ ).

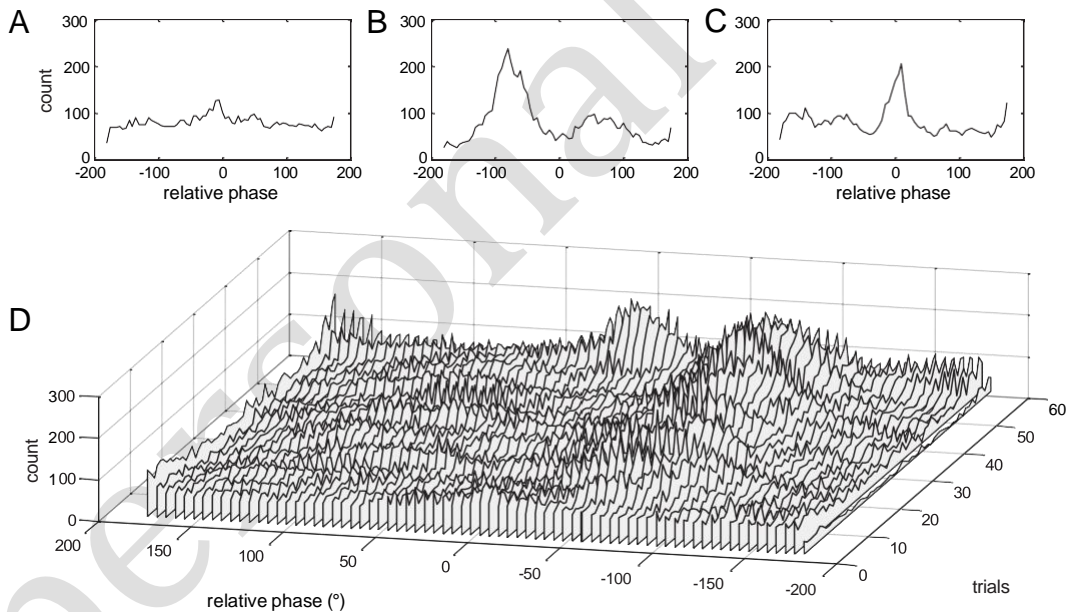


Fig. 4. RP Histograms. RP frequency distribution as a function of relative phase in a spontaneous trial (panel A), in a trial at the end of practice (panel B), and in a transfer trial (panel C). The evolution of the RP counts as a function of RP and trial (panel D) in the spontaneous (trials 1–5), practice (trials 6–55) and transfer (56–60) conditions.

error revealed a main effect of Experimental Block ( $F(6, 84) = 17.42, p = 0.001, \eta^2 = 0.55$ ). Simple contrasts documented that AE in the spontaneous block was higher than in all other blocks ( $p = 0.002$ ), and that at transfer it was higher than in B5 ( $p = 0.03$ ). A further 5 (Practice Block) ANOVA showed a main effect of Practice Block ( $F(4, 56) = 13.76, p = 0.0001, \eta^2 = 0.50$ ). Polynomial contrasts revealed that AE decreased as a function of Block following a linear trend ( $F(1, 14) = 27.42, p = 0.0001, \eta^2 = 0.66$ ).

**RP uniformity:** Fig. 5B portrays the RP uniformity as a function of Block. A 7 (Experimental Block) ANOVA on RP uniformity revealed a main effect of Experimental Block ( $F(6, 84) = 5.96, p = 0.0001, \eta^2 = 0.65$ ). Simple contrasts showed that the RP uniformity in the spontaneous block was higher than in blocks B2 to B5 and at transfer ( $p = 0.001$ ), and that at transfer it was higher only than in B5 and in the spontaneous block ( $p < 0.05$ ). A further 5 (Practice Block) ANOVA revealed a main effect of Practice Block ( $F(4, 56) = 3.398, p = 0.01, \eta^2 = 0.50$ ). Polynomial contrasts showed that the uniformity decreased linearly as a function of

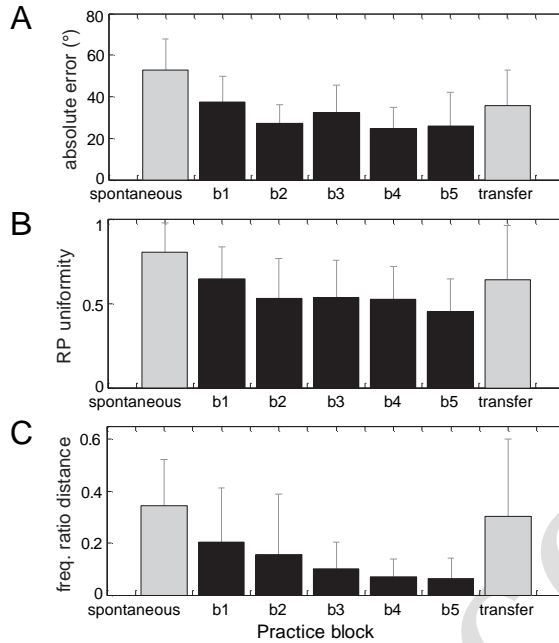


Fig. 5. Practice block effect. RP absolute error (panel A), RP uniformity (panel B), and Frequency Ratio Distance (panel C) as a function of Practice Block. The vertical bars illustrate between-participant standard deviations.

Block ( $F(1, 14) = 4.96, p = 0.04, \eta^2 = 0.60$ ).

### 2.2.3. Individual frequencies matching

Fig. 5C shows the Frequency Ratio Distance as a function of Block. A 7 (Experimental Block) ANOVA on this variable revealed a main effect of Experimental Block ( $F(6, 84) = 3.95, p = 0.001, \eta^2 = 0.53$ ). Simple contrasts showed that the Frequency Ratio Distance in the spontaneous block was higher than in all other blocks ( $p = 0.04$ ), and that transfer it was higher than in blocks B2 to B5 ( $p = 0.03$ ). A further 5 (Practice Block) ANOVA provided a main effect of Practice Block ( $F(4, 56) = 3.47, p = 0.013; \eta^2 = 0.20$ ). Polynomial contrasts indicated that the Frequency Ratio Distance diminished linearly as a function of Block ( $F(1, 14) = 5.32, p = 0.04, \eta^2 = 0.28$ ).

### 2.2.4. Coordination attractors

**Fixed point incidence:** Stable solutions arose in all dyads. In the spontaneous condition, they appeared in 32% of the trials ( $N = 24$ ). Using bins of  $45^\circ$  width, 63% of the stable solutions created during the spontaneous trials were located in the bins centered at  $\pm 45^\circ$ , 12% at  $\pm 90^\circ$ , 17% at  $\pm 135^\circ$ , and 8% at others values. The distribution was thus not uniform ( $\chi^2(3) = 43.69, p = 0.001$ ). Of interest, there were no fixed points in the bins centered at  $0^\circ$  and  $180^\circ$  PR. The FP incidence as a function of Block is displayed in Fig. 6A. A 7 (Experimental Block) ANOVA on this incidence revealed a main effect of Experimental Block ( $F(6, 84) = 22.85, p = 0.0001, \eta^2 = 0.62$ ). Simple contrasts indicated that the incidence was higher in all practice blocks than in the spontaneous ( $p = 0.001$ ) and transfer ( $p = 0.001$ ) block. A further 5 (Practice Block) ANOVA revealed a main effect of Practice Block ( $F(4, 56) = 6.33, p = 0.0001, \eta^2 = 0.31$ ). Polynomial contrasts showed that the FP incidence increased linearly as a function of Practice Block ( $F(1, 14) = 14.35, p = 0.002, \eta^2 = 0.51$ ). For the five last practice trials, 50% of bins were centered at  $\pm 90^\circ$ , 33% at  $135^\circ$ , and 10% at  $45^\circ$ . In addition, there was a reliable correlation between the FP incidence in the spontaneous trials and the transfer trials ( $r = 0.55; t(13) = 2.39; p = .02$ ).

**Fixed point stability:** The FP stability as a function of Block is illustrated in Fig. 6B. A 7 (Experimental Block) ANOVA on the FP stability revealed a main effect of Experimental Block ( $F(6, 71) = 4.51, p = 0.001, \eta^2 = 0.28$ ). Simple contrasts documented that the stability in the spontaneous condition was lower than that in B5 ( $p = 0.02$ ). In addition, at transfer the stability was lower than in blocks B4 and B5 ( $p = 0.03$ ). A further 5 (Practice Block) ANOVA indicated a main effect of Practice Block ( $F(4, 52) = 6.10, p = 0.0001, \eta^2 = 0.32$ ). Polynomial contrasts showed that the FP stability increased as a function of Practice Block as approximated by a linear trend ( $F(1, 13) = 13.45, p = 0.003, \eta^2 = 0.51$ ).

**Bistability incidence:** Fig. 6C portrays the bistability incidence as a function of Block. A 7 (Experimental Block) ANOVA on the bistability incidence revealed a main effect of Experimental Block ( $F(6, 84) = 5.02, p = 0.0001, \eta^2 = 0.26$ ). Simple contrasts documented that the incidence in the spontaneous block was lower than in all practice blocks ( $p = 0.04$ ), and that at transfer it was lower than in (practice) blocks B3 to B5 ( $p = 0.01$ ). A further 5 (Practice Block) ANOVA evidenced a main effect of Practice Block ( $F(4, 56) = 2.65, p = 0.04, \eta^2 = 0.16$ ). Polynomial contrasts showed that the bistability incidence increased linearly as a function of Practice Block ( $F(1, 14) = 6.93, p = 0.02, \eta^2 = 0.33$ ).

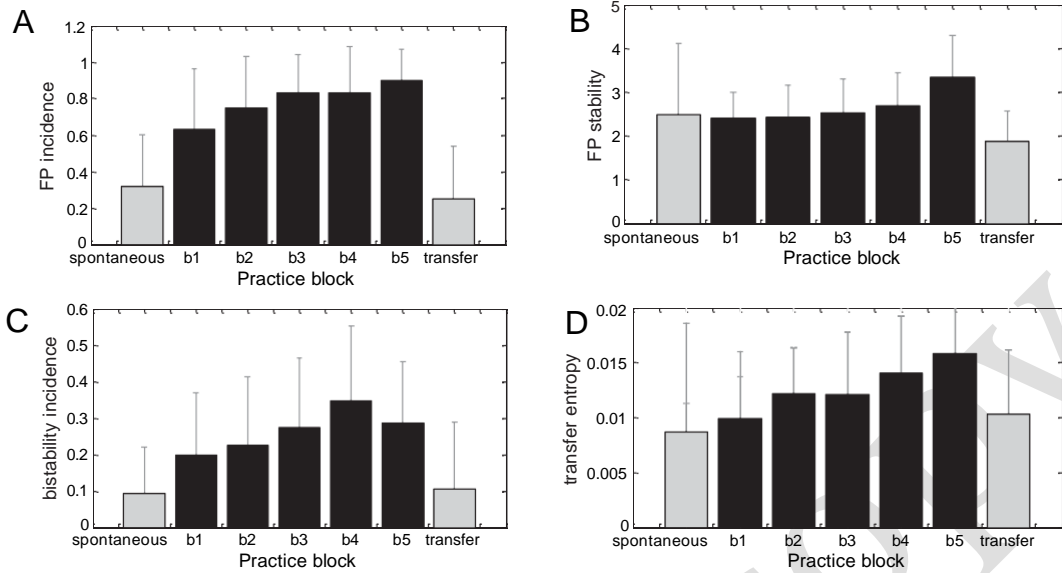


Fig. 6. Practice block effect. FP incidence (panel A), FP stability (panel B), Bistability incidence (as a proportion; panel C), Transfer Entropy (panel D) as a function of Block. The vertical bars illustrate between-participant standard deviations.

### 2.2.5. Information flow

Fig. 7D illustrates the Transfer Entropy as a function of Block. A 7 (Experimental Block)  $\times$  2 (Participant) ANOVA on transfer entropy revealed a main effect of Experimental Block ( $F(6, 168) = 11.12, p = 0.0001, \eta^2 = 0.28$ ). Simple contrasts documented that the entropy was lower in the spontaneous condition than in block B2 to B5 ( $p = 0.01$ ), and that at transfer it was lower than in block B4 and B5 ( $p = 0.002$ ). A further 5 (Practice Block) ANOVA evidenced a main effect of Practice Block ( $F(4,112) = 11.87, p = 0.0001, \eta^2 = 0.30$ ). Polynomial contrasts revealed that transfer entropy increased as a function of Block following a linear trend ( $F(1, 28) = 30.16, p = 0.0001, \eta^2 = 0.52$ ).

### 2.2.6. Sense of control and interviews

A 3 (Questions)  $\times$  5 (Practice Block) ANOVA on the sense of control revealed a main effect of Question only ( $F(2, 50) = 20.10$ ,

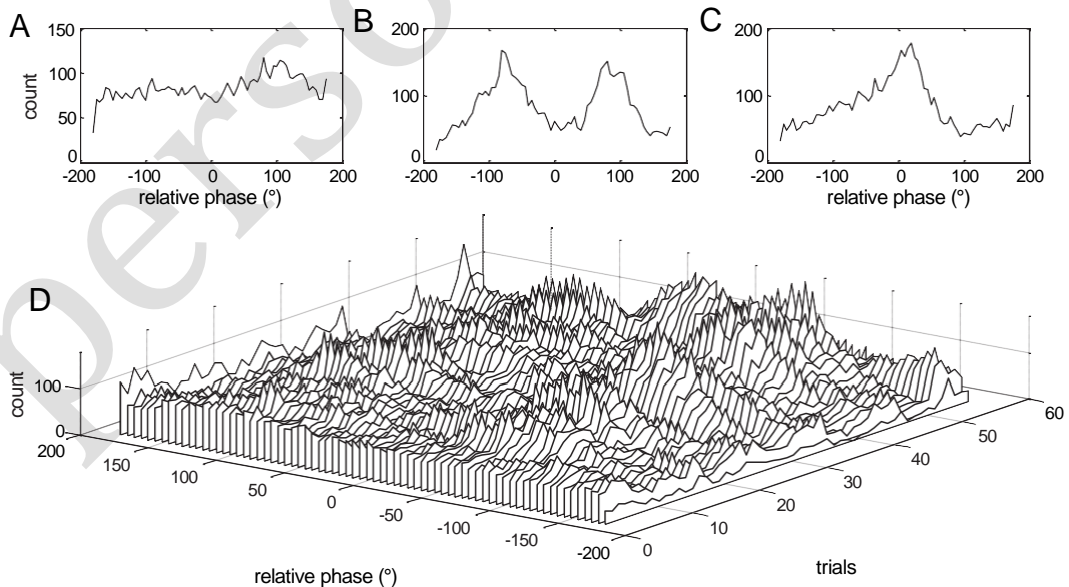


Fig. 7. RP Histograms. RP count as a function of relative phase in the spontaneous (panel A) block, at the end of learning (panel B), and at transfer (panel C). The evolution of the RP counts as a function of trial (panel D) in the spontaneous (trial 1–5), practice (trial 6–55), and transfer (trial 56–60) trials. The data of the practice trials stem from the no-choice trials.

$p = 0.001, \eta^2 = 0.79$ ). T-tests revealed that the level of we-control, which was assessed on a 0–100 scale, was significantly higher ( $M = 80, SD = 18.11$ ) than that of self-control ( $M = 56, SD = 25.17, p = 0.001$ ) and other-control ( $M = 52.18, SD = 18.95, p = 0.001, \eta^2 = 0.64$ ). The interviews conducted after the experimental session revealed that after the spontaneous, practice, and transfer conditions all participants were able to report what coordinate of the Lissajous dot was under his control. They also indicated that they sometimes tried to communicate this information to their partner by rapidly oscillating their joystick for a few instants.

### 2.3. Discussion

#### 2.3.1. Intrinsic dynamics and learning markers

In conformity with our hypotheses (1 and 2), our data clearly show that there was no intrinsic attractor prior to learning. In classic bimanual coordination paradigm, where intrinsic patterns arises, the frequency ratio distance amounts to 0 (i.e., there is 1:1 frequency matching), RP uniformity to about 0.03 for  $0^\circ$  and to 0.05 for  $180^\circ$ ; the incidence of fixed points is close to 100%. In our task, the frequency matching precondition is not fulfilled: the frequency ratio distance amounts to 0.38. RP uniformity is at 0.7, encompassing thus 70% of possible RP range; the fixed points incidence is 30% and none of these ghost attractors was located at  $0^\circ$  or  $180^\circ$  PR.

The functional importance of such rising and vanishing ghost attractors was supposed to offer an initial background from which new attractors may arise, be explored without being (steadily) adopted (Deco, Senden, & Jirsa, 2012). In our data, as indicated by the reliable correlation between the FP incidence during the spontaneous trials and the transfer trials, the emergence of attractors in the spontaneous trials was correlated with the ability of learning during practice.

As expected for practice, the frequency ratio converged toward 1-to-1, and the information gathered from the partner, assessed by transfer entropy, increased as the partners learned to co-produce the required Lissajous figure (Hypothesis 3 and 4). After the experimental session, participants were also able to verbalize which coordinate of the dot movement was under his/her control (Hypothesis 6). A closer look revealed that the stability of the fixed point(s) increased, and that the incidence of bistability went up. Overall, two attractors emerged approximately at the two possible task solutions ( $90^\circ$  and  $-90^\circ$  RP). How may learning take place despite the disturbance ~ correction challenge? Our intuition is that transiently locked RPs close to the required RP may be intentionally selected for further stabilisation. One possibility is that both partners recognize that the closer they are to the goal, the less likely the other will change his/her ongoing movements. If the dot is close to the required trajectory, only small disturbances ~ corrections are expected from both partners, and inversely.

#### 2.3.2. Learning performance

The learning in our task was, however, far slower, performance accuracy far lower, and the inter-individual variability higher than that documented in inter-limb coordination learning under the guidance of Lissajous figure by a single person, where after 5 min of practice learners displayed absolute errors of about  $10^\circ$  with inter-individual standard deviations of about  $1^\circ$  (Kovacs et al., 2009). In our data, for the five last practice trials, only 50% of the fixed points were located at  $\pm 90^\circ$ , 33% appeared at  $\pm 135^\circ$  and 10% at  $\pm 45^\circ$ . Two complementary explanations may be provided to explain this reduced learning performance. First, the binding based on the neural information exchanged between two limbs of a single person is stronger than the binding through visual information between the limbs of two distinct individuals (cf. Richardson et al., 2008; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998). The second explanation lies in the lack of an objective visual model: in contrast to Kovacs' work, no static circle was displayed and thus objective error specification between the Lissajous model and the dot was not possible. We abstained from displaying a model as we wanted our partners to subjectively co-define error, that is, to distinguish when acceptable and when to-be-reduced divergence of the Lissajous dot from circle occurred.

#### 2.3.3. Variability preservation

The incidence of bistability rose as a function of practice, implicating that the learning systems tended to preserve the opportunity of switching between  $90^\circ$  and  $-90^\circ$ , instead of increasing behavioral predictability by spontaneously selecting a unique pattern. Variability preservation may be an advantageous feature: Working on locomotion learning, evolutionary robotics (Lehman & Stanley, 2011) showed that bipedal robots controlled by an algorithm encouraging the production of behaviors diverging from prior ones learned better gait patterns than the robots controlled by an algorithm favoring behaviors closest to the environmental requirement. The authors explained that variability preservation is advantageous in complex tasks, where the fitting search does not reward the stepping stones in the search space that ultimately lead to the optimal outcome.

#### 2.3.4. Generalization at transfer

After the stabilization of the more or less circular Lissajous figure ( $\pm 90^\circ$  RP), the participants co-produced an untrained diagonal slope ( $0^\circ$  or  $180^\circ$  RP): as expected (Hypothesis 5), learners succeeded in capturing information from practice that was generalizable to the unlearned pattern. When a participant had found out that he/she is controlling, say, the vertical position of Lissajous dot, it was possible for him/her to exploit that information in the production of other Lissajous figures. This observation may enrich the long-lasting debate opened in individual learning studies about the difference between the feedback coming from two distinct limbs and from Lissajous figures (e.g., Wilson et al., 2010). When partners watch each other's limb, available data suggest no transfer between  $0^\circ/180^\circ$  RPs and  $90^\circ$  RPs (Schmidt et al., 1998). Lissajous feedback allowed transfer prohibited in these above-mentioned typical situations.

### 2.3.5. *The prevailing feeling of we-control*

Individuals attributed the motor outcome to we-control: They experienced the whole dyad as a unit of agency. The experience of we-control did not change as accuracy and stability increased. The we-control was thus not cued by the congruence between the anticipated and actual Lissajous shape, as it is often the case for the sense of I-control in individual situations (for a review, see Pacherie, 2012), but rather by the reciprocal dependency in the production of the motor outcome. It is worth noting that several dyads did not describe the control as symmetric: Post-experimental interviews suggested a division of labor spontaneously emerging in 27% of the groups in which a partner described himself as “just moving the joystick” and the other as “performing the correction task”.

## 3. Experiment 2

### 3.1. *Introduction*

The abovementioned division of labor seems adequate to overcome the disturbance ~ correction challenge, originating from the unpredictability of one's partner's adjustments. When a partner takes full control of corrective process in the inter-personal coordination task, the oscillations of the other are not disturbed by attempts of error correction. They thus supposedly become more regular and thus more predictable. In a multi-player number guessing game, Roberts and Goldstone (2011) indeed showed that some players opted for role differentiation in order to foster predictability. In the next experiment we test thus two hypotheses: If allowed to make such a choice, would partners prefer to take full, unilateral control of the correction by asking his/her partner to close his/her eyes in the next trial (Hypothesis 1)? In the eyes-closed partner condition, would the accuracy and stability of the Lissajous figure be higher than in the eyes-open partner situation (Hypothesis 2)? With an eyes-closed partner, would the movement frequency be less variable than with an eyes-open partner because the motion is not perturbed by correction processes (Hypothesis 3)?

### 3.2. *Method*

#### 3.2.1. *Participants*

Fourteen pairs of unpaid volunteers, all males, aged about 25 ( $\pm$  5) years, self-claimed right-handed, took part in the study. All participants were undergraduate students at the Faculty of Sport Sciences at Toulouse, France. They were naïve to the purpose of the study, reported normal or corrected-to normal visual acuity and had no physical impairment impeding the required pattern production. None of the participants had participated in Experiment 1. The study was approved by the local ethical committee of Paul Sabatier University and participants provided a written informed consent in accordance with the Helsinki Declaration.

#### 3.2.2. *Material and procedure*

The material and apparatus were identical to those described in Experiment 1 but the procedure was slightly modified. No questionnaire of the sense of control was given. Instead, we tested whether having full, unilateral control of error correction would be the preferred option. To this aim, after five spontaneous trials, nine 5-trial practice blocks were administered. Block 1, 3, 5, 7 and 9 corresponded to a No-Choice condition, and block 2, 4, 6 and 8 to a Choice condition. In the No-Choice blocks, both participants watched the screen; in the Choice blocks, a participant was asked to decide if he/she wished his/her partner to open or close the eyes in next trial. A single participant per dyad was drawn by lot to play the role of decision-maker for the whole experiment. The decision-maker was urged 'to make his/her choice on his/her own, with regard to his/her preference only'. Five transfer trials (i.e., 0° and 180°) ended the study. The whole experimental session lasted about 50 min.

#### 3.2.3. *Data reduction and statistical analysis*

Data reduction was identical to those in Experiment 1. Statistical analyses comported several changes. First, we aimed to replicate the results from Experiment 1, referred to as the replication analysis below, by analyzing the spontaneous block together with the five no-Choice blocks and the transfer block. As above, a 7 (Experimental Block = {spontaneous, B1, B2, B3, B4, B5, transfer}) ANOVA followed by a 5 (Practice Block = {B1, B2, B3, B4, B5}) ANOVA and contrasts were performed. Then, the statistical analysis additionally focused on the Choice and No-Choice Blocks, referred to below as the choice analysis. For each Choice block, trials were separated as a function of the decision-makers wish (i.e., eyes-open and eye-closed partner). There was thus an additional factor (Choice), with three levels: no choice (from the no-Choice blocks), eyes-open partner (from the Choice blocks), and eye-closed partner (from the Choice blocks). The statistical analysis focused on Choice and No-Choice Blocks. The first four No-Choice blocks were selected for this analysis. A 3 (Choice = {eyes-closed partner, eye-opened partner, and no choice}  $\times$  4 (Block = {B1, B2, B3, B4}) ANOVA was carried out on all dependent variables, with repeated measures on second factor, followed by pairwise comparisons. Finally, a 4 (Block) ANOVA was undertaken on the percent of eyes-closed partner decisions. If appropriate, this analysis was complemented with orthogonal simple contrasts.

Given that the coordination dynamics was repeatedly bi-stable, the RP uniformity was removed as an index of stability because switches between (stable) patterns at 90° and -90° RP gives rise to high RP uniformity. For each Choice block, we computed the percent of trials where the decision-maker asked his partner to keep eyes closed. In order to assess movement frequency consistency (viz. Hypothesis 3), the power at the peak in the power spectrum was extracted: the higher the peak power, the more consistent the movement frequency. For all results, only significant effects at  $p = 0.05$  are reported along with corresponding estimates of effect size ( $\eta^2$ ). When the sphericity assumption was violated, the Greenhouse-Geisser correction was used.

Table 2

Replication analyses. Statistical results in Experiment 2, replicating the results of Experiment 1. AE: absolute error, FRD: frequency distance ratio, FPi: fixed point incidence, FPs: fixed point stability, BI: b-stability incidence, TE: transfer entropy.

	7 (Experimental Block) ANOVA			5 (Practice Block) ANOVA			
	F(6,78)	p-value	$\eta^2$	F(4,52)	p-value	$\eta^2$	$\eta^2$
AE	0.49	0.001	0.45	4.51	0.003		0.26
FRD	13.37	0.0001	0.51	5.78	0.001		0.31
FP <sub>i</sub>	23.90	0.001	0.65	12.92	0.001		0.99
FP <sub>s</sub>	3.14	0.002	0.23	4.41	0.004		0.25
BI	2.95	0.01	0.19	Ns	ns		ns
TE	2.43	0.03	0.16	3.50	0.013		0.21

### 3.3. Results

#### 3.3.1. Visual inspection of the data

All RPs collected in the experiment, pooled over participants, are displayed in histograms in Fig. 7. In the spontaneous condition (panel A), the RPs histogram is approximately flat, indicating that no preferred pattern exists; following practice (panel B), it is bimodal, showing two humps at about  $90^\circ$  and  $-90^\circ$  RP. At transfer (panel C), the RPs histogram displays a maximum at  $0^\circ$ . The evolution of the RPs frequency distribution over the whole experiment (panel D) depicts a rise of a preferred RPs at about  $\pm 90^\circ$  followed by the preferred RP shift toward  $0^\circ$  at transfer.

#### 3.3.2. Replication analysis.

The statistical results for all variables analysed in the replication analysis (i.e., no choice condition) were very similar (most often identical) to those in Experiment 1. For brevity, the corresponding main results are not spelled out in detail but are summarized in Table 2.

#### 3.3.3. Choices and interviews.

A reliable analysis of eye-closed and eye-opened choices depends on the availability of a sufficient number of observations for each of the conditions. There were 70 choice trials in each block ( $14 \text{ pairs} \times 5 \text{ trials} = 70$ ). The percent of choices for eyes-closed partner was 54% in B1, 47% in B2, 56% in B3, 47% in B4, and 47% overall. We thus had at least 33 and at most 39 choices for the eyes-closed partner (and at most 37 and at least 31 for the eyes-open partner) in each Block. A 4 (Block) ANOVA on the percent of choices provided no significant results. Each decision-maker provided at least two choices for the least often selected option, allowing us to collect required statistics for each dyad.

Interviewed after the experimental session, decision makers remarked that the eyes-closed partner condition was clearly easier but somewhat absurd, because “it is a collective learning task”, and irrelevant, because the partner was unable to progress. Asked how they came to coordinate, participants reported to have focused on a specific point on the screen where the Lissajous figure was displayed, instead of tracking the Lissajous dot visually.

#### 3.3.4. Choice analysis

**3.3.4.1. Coordination accuracy: absolute error.** The AE as a function of Choice and of Block is displayed in Fig. 8. A 3 (Choice)  $\times$  4 (Practice Blocks) ANOVA on AE showed a significant Choice  $\times$  Block interaction ( $F(6, 78) = 3.84, p = 0.002, \eta^2 = 0.23$ ). Polynomial contrasts revealed that the AE decreased as a function of Practice Block following a linear trend in no choice and eyes-open condition

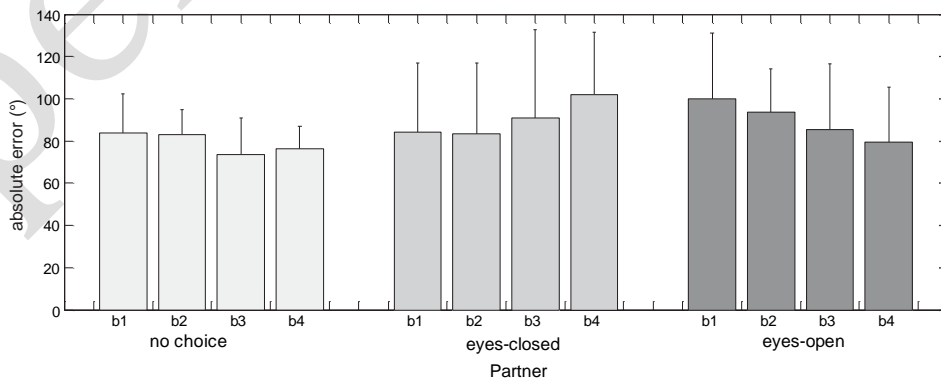


Fig. 8. Absolute error at practice. Absolute error as a function of Choice (no choice, eyes-closed partner, eyes-open partner) and block (b1, b2, b3, b4). The error bars represent the between-participant standard deviations.

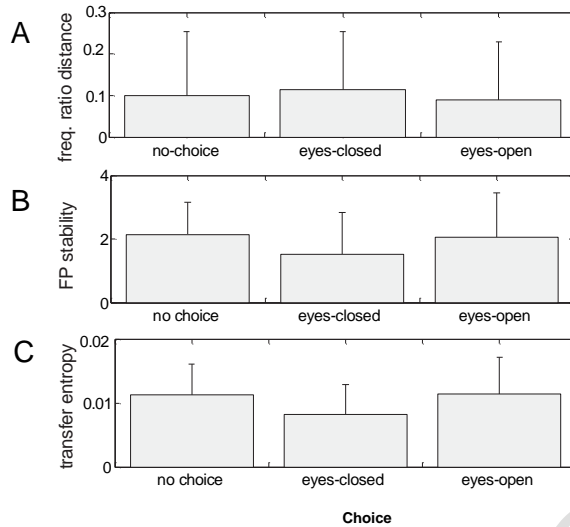


Fig. 9. Choice effect at practice. Frequency Ratio Distance (panel A), FP stability (panel B) and Transfer Entropy (panel C) as a function of Choice (no choice, eyes-closed partner, eye-open partner). The vertical bars illustrate between-participant standard deviations.

( $F(1, 13) = 4.67, p = 0.04, \eta^2 = .29$ ;  $F(1, 13) = 5.76, p = 0.03, \eta^2 = 0.31$ ). Pairwise comparisons documented that AE in B4 was higher for the eyes-closed partner than for the eyes-open partner condition ( $p = 0.03$ ).

**3.3.4.2. Individual frequency matching. Frequency ratio distance:** The Frequency Ratio Distance as a function of Choice and of Block is illustrated in Figs. 9A and 10A, respectively. A 3 (Choice)  $\times$  4 (Practice Blocks) ANOVA evidenced a main effect of Choice ( $F(2, 26) = 3.86, p = 0.03, \eta^2 = 0.25$ ) and of Block ( $F(3, 39) = 4.56, p = 0.01, \eta^2 = 0.45$ ). Pairwise comparisons documented that the Frequency Ratio Distance was higher in the eyes-closed partner condition than in eyes-open partner condition ( $p = 0.04$ ). Polynomial contrasts showed that the Frequency Ratio Distance decreased as a function of Practice Block following a linear trend ( $F(1,13) = 9.81, p = 0.01, \eta^2 = 0.47$ ).

**Peak power:** A 3 (Choice)  $\times$  4 (Practice Blocks)  $\times$  (Participant) ANOVA on peak power evidenced a main effect of Choice ( $F(2,26) = 3.94, p = 0.03, \eta^2 = 0.52$ ). Further t-tests revealed that the peak power was slightly higher in the eyes-closed than in eyes-

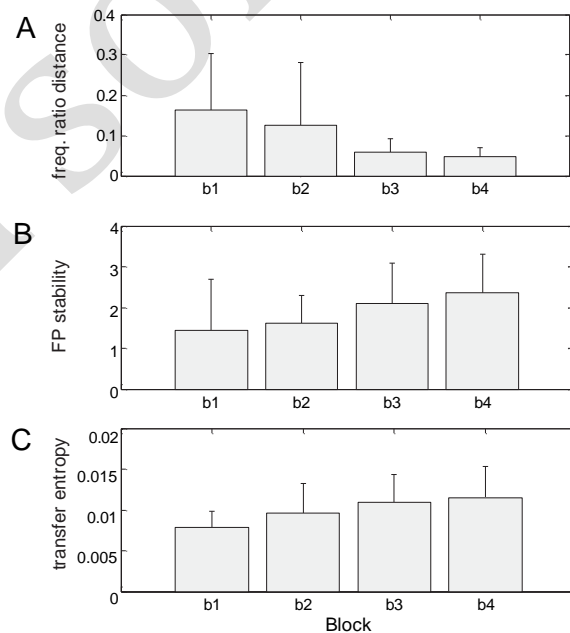


Fig. 10. Block effect at practice. Frequency Ratio Distance (panel A), FP stability (panel B) and Transfer Entropy (panel C) as a function of Block (b1, b2, b3, b4). The vertical bars illustrate between-participants standard deviations.

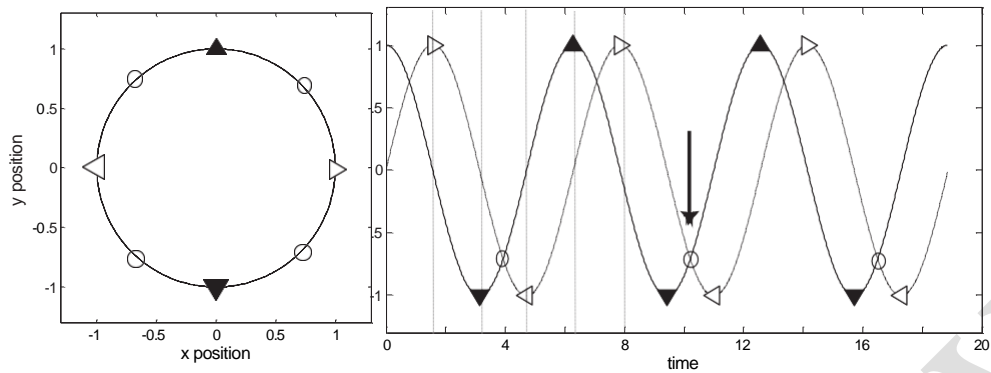


Fig. 11. Lissajous figure. Lissajous figure (left panel) and corresponding positions of  $x$  and  $y$  oscillators (solid and dotted line, respectively; right panel). Dotted vertical lines specify the 0,  $\frac{1}{4}$ ,  $\frac{1}{2}$ , and  $\frac{3}{4}$  of a cycle of the oscillator illustrated by dotted lines. Reversal points are pictured by triangle markers and oscillators intersections by ellipsoids markers. Arrows point out an intersection.

open partner condition ( $t(13) = 2.18, p < 0.05$ ).

**3.3.4.3. Coordination attractors. Fixed point incidence:** A 3 (Choice)  $\times$  4 (Practice Blocks) ANOVA evidenced a main effect of Block ( $F(3, 39) = 4.15, p = 0.01, \eta^2 = 0.24$ ) and of Choice ( $F(2, 26) = 5.02, p = 0.01, \eta^2 = 0.28$ ). Polynomial contrasts showed that the FP incidence increased as a function of Practice Block following a linear trend ( $F(1, 13) = 7.73, p = 0.02, \eta^2 = 0.37$ ). T-tests using Bonferroni correction documented that the FP incidence at B2 was lower in the eyes-closed condition than in the eye-open partner condition ( $p < 0.05$ ).

**Fixed point stability:** Figs. 9B and 10B show the FP stability as a function of Choice and of Block, respectively. A 3 (Choice)  $\times$  4 (Practice Blocks) ANOVA evidenced a main effect of Choice ( $F(2, 26) = 5.02, p = 0.01, \eta^2 = 0.28$ ) and of Block ( $F(3, 39) = 4.03, p = 0.01, \eta^2 = 0.24$ ). Pairwise comparisons revealed that the FP stability was lower in the eyes-closed partner condition than in both the eyes-open partner condition ( $p = 0.002$ ) and the no choice condition ( $p = 0.001$ ). Polynomial contrasts indicated that the fixed-point stability increased linearly as a function of Practice Block ( $F(1, 13) = 7.04, p = 0.02, \eta^2 = 0.35$ ). There was no significant effect of choice on the bistability incidence.

**3.3.4.4. Information measure.** Transfer entropy as a function of Choice and of Block is portrayed in Fig. 9C and 10C, respectively. A 3 (Choice)  $\times$  4 (Practice Blocks)  $\times$  2 (Participant) ANOVA evidenced a main effect of Choice ( $F(2, 26) = 7.19, p = 0.003, \eta^2 = 0.36$ ) and of Block ( $F(3, 39) = 5.17, p = 0.004, \eta^2 = 0.28$ ). Pairwise comparisons indicated that the transfer entropy was higher when the partner had the eyes closed than in the eyes-open partner ( $p = 0.001$ ) and the no choice ( $p = 0.001$ ) conditions. Polynomial contrasts showed that transfer entropy increased as a function of Practice Block (see Fig. 11D) following a linear trend ( $F(1, 13) = 7.05, p = 0.02, \eta^2 = 0.55$ ).

#### 3.4. Conclusion

For the no-Choice blocks, Experiment 2 largely replicated the results from Experiment 1. For the Choice blocks, contrary to our Hypothesis 1, decision-makers displayed no preference for the eyes-closed partner over the eyes-open partner condition. Contrary to our Hypothesis 2, coordination patterns were less stable, less accurate, and offered less information when a partner closed the eyes during performance. Peak power was slightly higher in the eyes-closed partner condition, signaling that the movement frequency of both partners was slightly more stable in eyes-closed partner condition. Quite surprisingly, choosing full, unilateral control over error correction in the Lissajous figure did not benefit coordination performance, despite the slightly higher movement frequency stability.

### 4. General discussion

We investigated how learning develops within two human partners asked to draw a circle together in a plane under the guidance of Lissajous feedback. Each partner controlled one (different) direction so that successful performance required the partners to, at least, coordinate the timing of their movements. In such a task, whether a partner's movement is corrective or disruptive depends on the simultaneous but unknown movements of the other. Our goal was to investigate whether the partners learned a solution to the disturbance  $\sim$  correction challenge. The data evidenced that learning developed in this situation (Experiment 1 and 2). To our surprise, when the control of the error correction process was distributed over two participants, performance accuracy and stability were higher as compared to the situation with unilateral control (Experiment 2).

#### 4.1. Intermittent phase locking and stabilization process

Using our task, we intentionally confronted individuals with weak environmental and task constraints in order to open up an

experimental window into intermittent phase locking. Intermittency refers to the incidental arising and vanishing of stable fixed points from trial to trial. The weakest constraints were provided when no instruction about the outcome to be co-produced was offered, so that the partners were free to explore all possible motor outcomes. Nonetheless, stable fixed points did appear in 32% of the trials, implying that a stable coordination pattern resulting in phase locking can take place without explicit instructions. These transient attractors appeared most often about  $\pm 45^\circ$  bins, suggesting that spontaneously, the coordination system coupled via Lissajous feedback tends to linger in these two regions of the RP space. Much work is devoted these days to the functional importance of intermittent phase locking. It would offer the coordination system the possibility of visiting a set of possible solutions, without being trapped inside a unique attractor, which may be suboptimal or may become so in the future (Friston, 1997; Kelso, 2012; Kelso & Tognoli, 2007; Tognoli & Kelso, 2014). Our tentative proposal is that intermittent phase locking paves the way for selection during practice. When both actors happen to produce a circular trajectory, they tend to maintain it together and reproduce it in the next trial. In contrast, when an inaccurate pattern appears, both partners tend to disturb it in order to seek for another perceptual-motor solution.

These findings further testify to, and deepen our understanding of how variability functions in motor learning. Far from being meaningless and undesirable fluctuations, variability is fully involved in the shaping of learning process (Bassett et al., 2011; Kostrubiec, Tallet, & Zanone, 2006; Trommershäuser, Maloney, & Landy, 2008; Wu, Miyamoto, Castro, Ölveczky, & Smith, 2014).

#### 4.2. Learning under distributed control of error correction

How does learning occur in a social system where control is distributed over all its participants that have only partial knowledge of what the other partners are doing? A possible answer, roughly inspired from swarm robotics (Kube & Bonabeau, 2000) is that if the partners learn to obey an adequate, locally checkable constraint, a coordination pattern may stabilize at the collective level. A constraint is locally checkable if an individual partner can ratify it on its own. In our task, such a constraint may specify the state of an individual hand relative to the state of the Lissajous dot. For instance, if a partner (dotted line in right panel of Fig. 11) finds out that when the dot is closest to the screen edge (ellipsoids in Fig. 11), and his hand reach  $3/8$  of its cycle (right arrow in the right panel in Fig. 11), a circular figure (left panel in Fig. 11) is likely to be produced. Of course, if his/her partner does not utilize the same rule, success is jeopardized. For this reason, the local rule is not full-proof, similar to heuristics studied in psychology. Heuristics are “rules of thumb” used under uncertainty, exploiting readily discriminable information to help achieve an acceptable performance. Once such a local rule learned, it may be readjusted for transfer.

#### 4.3. Control of error correction and its feeling

Our manipulation of the choice of control of the error correction provided surprising findings. The first surprising result is that learners performed better when the control of Lissajous figure was distributed over two participants than when only one participant was able to adjust and control the figure. As compared to the bilateral, distributed control of error correction, in the unilateral, full control case, pattern accuracy and stability were lower, individual frequencies were less well locked, and transfer entropy was weaker. Similar results were pointed out (Skewes, Skewes, Michael, and Konvalinka, 2015) in another experimental paradigm, where dual to individual performance was compared (ie. a dyad vs. an individual performing alone; Shea et al, (1999); Shebilskem, Regian, Arthur, & Jordan, 1992). These findings stand in contradiction to our expectation, namely that the removal of the disturbance ~ correction challenge would facilitate error reduction. We offer an explanation thereto. On average, distributed control leads to better performance as compared unilateral one, because in each dyad the better partner compensates for his/her worse co-actor. Consequently, two identical partners perform as well when coupled bi-directionally as in when coupled unidirectional but two distinct bi-directionally coupled partners perform like the best one.

The second surprising finding is that the decision-maker did not show a preference for full unilateral control of error correction (i.e., asking the partner to close his eyes). Whatever the theoretical framework, humans are described as displaying intrinsic preference for control: ‘man strives to be a causal agent’ (Bennett, 1998; DeCharms, 1968, p. 269; Langer, 1975; Seligman, 1970; Suzuki, 1997). How then can the lack of preference for full unilateral control of error correction in our data be explained? A possible interpretation is that decision-makers did not suffer from the distribution of control of error correction in eye-open condition because they attributed it to the broader social unit they belonged to. In Coordination Dynamics parlance, the control operated at the collective level of relative phase dynamics (Kelso et al., 2013). Eyes-open condition brings no less control as compared to eyes-closed one, it brings control at the collective level of coordination dynamics, where both partners act as an indissociable whole. Inter-personal coordination is known to establish the feeling of togetherness (De Coster, Verschuere, Goubert, Tsakiris, & Brass, 2013; Lakens, 2010; Miles, Nind, Henderson, & Macrae, 2010; Novembre, Ticini, Schutz-Bosbach, & Keller, 2012; Valdesolo & DeSteno, 2011; Wiltermuth & Heath, 2009) and to boost social trust (Launay, Dean, & Bailes, 2013). Our data complete these findings by showing that inter-personal coordination also promotes the feeling of we-control. The key contribution in this work was to bring to light why the hypothesis of correction ~ disturbance challenge led to incorrect predictions: Under its umbrella, individuals were described as acting as separable individuals, whereas in reality they act as a unique whole in dyadic condition.

## 5. General conclusion

We investigated how learning develops in a broad learning unit where the control of a movement outcome, a specific Lissajous figure, is distributed over two participants. In the absence of any instruction about the Lissajous figure shape, stable states

incidentally arose and vanished. When a specific Lissajous figure was required, relative phase converged over trials towards the required value(s). Participants had no preference for full or unilateral control of error correction, and distributed control resulted in higher stability and accuracy.

## 6. Author contributions

VK participated in the design of the study and data collection. VK and RH analysed the results and drafted the manuscript. All authors critically reviewed and edited the manuscript for important intellectual content, and all authors approved the final manuscript.

## 7. Compliance with ethical standards

*Conflict of interest:* The authors declare that they have no conflict of interest.

*Ethical approval:* All procedures performed in studies involving human participants were in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

*Informed consent:* Informed consent was obtained from all individual participants included in the study.

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