

## Individual and dyadic rope turning as a window into social coordination

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### ABSTRACT

The spontaneous and intentional movement coordination between peoples is well understood. Less is known about such interactions when the coordination is subordinate to the task and when the task involves, next to vision, mechanically induced haptic and kinesthetic coupling between dyadic partners. We therefore investigated dyadic jump rope turning. Fifteen dyadic pairs conjointly turned a jump rope to which five markers were equidistantly attached, and whose movements were recorded in 3D. In addition, each participant turned one side of the rope while the other side was quasi-fixed in an individual baseline condition. The participants' goal was to turn the rope regularly and smoothly. Individual spontaneous turning frequencies differed substantially across participants. Yet, dyadic pairs spontaneously turned the rope at a common frequency, indicative of frequency entrainment. The dyadic rope rotations were less variable despite weaker between near-hand marker coordination than the individual rope rotations, and the degree of performance improvement was most pronounced for participants who were paired with a partner who performed better in the individual condition. The direction and relative strength of the coupling between partners varied substantially across dyads, but the degree of coupling asymmetry had no substantial effect on the rope tuning quality. The absolute degree in which dyadic partners adjusted to each other, however, scaled moderately with their turning performance. Although the individual performances did not predict the dyadic performances, the difference in individual performance between dyadic partners had some predictive value for the dyadic performance. In combination, these results indicate that the partners were functionally adapting to each other in order to satisfy the task goal and suggest that the relative performance differences rather than the individual performances has predictive value for conjoint action.

### 1. Introduction

The investigation of how individuals interact and conjointly perform tasks has been pursued along various lines (cf. Schmidt, Fitzpatrick, Caron, & Mergeche, 2011). One approach that has become quite popular over the last decades holds that a common

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coding, or representational format, underlies action and perception (Prinz, 1997; Sebanz, Bekkering, & Knoblich, 2006), which enables actors and observers to share representations. This, in turn, permits individuals to predict the timing and outcome of perceived actions, as well as establish and maintain inter-individual coordination by integrating another's anticipated action into one's own (Knoblich, Butterfill, & Sebanz, 2011; Sebanz et al., 2006). An alternative, dynamical approach explicitly seeks to identify the phenomenological laws underlying the formation of behavioral (coordination) patterns, and answer the question of whether and under what conditions individuals adapt their movements to each other spontaneously or in accordance to specific task instructions. This latter approach, which was initially developed in the context of intra-individual inter-limb coordination (Beek, Peper, & Stegeman, 1995; Haken, Kelso, & Bunz, 1985; Kelso, 1995; Turvey, 1990), has repeatedly shown that when two individuals simultaneously perform and perceive each other's rhythmical movements, the coordination between them is confined to a limited number of coordination modes (Richardson, Lopresti-Goodman, Mancini, Kay, & Schmidt, 2008; Schmidt & O'Brien, 1997; Turvey, 1990; for a review, see Schmidt & Richardson, 2008). For instance, in their paradigmatic study, Schmidt, Carello, and Turvey (1990) asked paired participants to swing one of their legs while looking at the other participant's swinging leg. In a series of experiments they found that the in-phase swinging mode was more stable than the anti-phase mode and observed transitions from the anti-phase mode to the in-phase one (but not the reverse) with increasing movement frequency as well as signs of hysteresis. Indeed, for comparable experimental settings, the same coordination phenomena as observed in individual inter-limb coordination (i.e., differential stability of the in-phase and anti-phase pattern, phase transitions, hysteresis, etc.; see Kelso, 1995, for a review) appear in inter-individual limb coordination, even though the coupling between the moving components is weaker in inter-person than in intra-person coordination (Richardson et al., 2008; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998). Regardless, the key observation, namely that there are only a few states in which the partners' coordinated behavior is found most of the time, and that this is largely independent of whether the coordination is established intentionally or arises spontaneously, has since been confirmed in numerous studies (see Schmidt & Richardson, 2008, for a review).

Although the research on social coordination has generated important insights – above all, that social coordination constitutes a pattern formation process – it remains yet to be seen to which degree several of its key phenomena can be generalized across the multitude of tasks that two individuals may perform conjointly (Lagarde, 2013; Richardson et al., 2015). In that regard, the task context that initially inspired many studies deviates from daily inter-individual tasks in several ways. First, in paradigmatic social coordination studies, the dyadic partners either do not strive to achieve a common goal (they merely oscillate their limbs) or the goal is defined in terms of particular coordinative states (for instance, 'oscillate your limbs in phase'). In these cases, means and ends collide. In ordinary tasks the actors typically move together with the aim to co-jointly achieve a common goal, such as to displace furniture, dance a tango, or play doubles in racket sports, to name a few. In such cases, coordinated movement is a means to an end. An example of the latter case is crew rowing, where the aim is to transfer energy into boat velocity, and which is done more efficiently in the anti-phase coordination mode than in the in-phase mode (de Brouwer, de Poel, & Hofmijster, 2013). Another documented example is inter-personal aiming (Mottet, Guiard, Ferrand, & Bootsma, 2001), in which two individuals together perform a Fitts' task (Fitts, 1954; Fitts & Peterson, 1964). In the joint task version, one person moved the pointer as the other moved the targets, and the participants spontaneously adopted an anti-phase coordination between the pointer and target movements, particularly so when the accuracy constraints were severe. Second, while in many tasks successful performance requires a certain degree of synchrony between the two partners, maximizing synchronization (but not coordination) may hamper task success in other tasks. For instance, Masumoto and Inui (2013) studied interpersonal periodic force production. They reported that dyads performed the task by synchronizing their force production, but at the same time, were complementary in terms of the amount of force generated. That is, low maximal forces generated by one partner were associated with high maximal force generated by the other partner. This strategy thus entails an anti-correlation in the force amplitudes produced. Similarly, any 'signaling' of one partner of his/her intentions to the other (Sacheli, Tidoni, Pavone, Aglioti, & Candidi, 2013; Vesper, Van Der Wel, Knoblich, & Sebanz, 2011) by definition entails a departure from (perfect) synchrony. In fact, the latter example can be cast in terms of symmetry breaking, that is, the deviation from perfect similarity of the coordinating components (be it due to structural/physical or task constraints; Lagarde, 2013). Third, in most studied instances of social coordination, the coupling between the two actors is visual. While vision undoubtedly plays an important role in many tasks performed conjointly, there are multiple instances where one actor obtains information about the other's activity through haptic (e.g., Ganesh et al., 2015; van der Wel, Knoblich, & Sebanz, 2011) as well as auditory information, as is typically the case in musical performances (Chang, Livingstone, Bosnyak, & Trainor, 2017; Keller, Novembre, & Hove, 2014). Different time scales are associated with information stemming from and flowing through different (sensory) media. For instance, the delays associated with vision and proprioception are estimated to be about 100–120 ms and 50–60 ms, respectively (Cameron, de la Malla, & López-Moliner, 2014). Whether the effect of a delay is facilitative or disruptive depends on the value of the delay relative to the predominant task-inherent time scale involved (Tass, Kurths, Rosenblum, Guasti, & Hefter, 1996). These differences notwithstanding, in paradigmatic sensorimotor coordination tasks people are readily able to establish a 0° (and 180°) relative phasing with a periodic sensory event regardless of whether the latter is visual and/or auditory and/or haptic, even though the stability of the performed pattern depends on the modality of the event (Armstrong & Issartel, 2014; Elliott, Wing, & Welchman, 2010; Kelso, Fink, DeLaplain, & Carson, 2001; Lagarde & Kelso, 2006; Repp & Penel, 2004; Varlet, Marin, Issartel, Schmidt, & Bardy, 2012). That is, in these experimental paradigms it matters little if at all through which medium the coupling is achieved. In more ecological task settings, however, deviations from the paradigmatic observations have been reported. In crew rowing, already mentioned above, the partners are mechanically coupled through the boat. Cuijpers and colleagues reported that the in-phase and anti-phase pattern were equally variable, even though the deviation from the intended relative phase was larger in the anti-phase pattern than in the in-phase pattern (Cuijpers, Zaai, & De Poel, 2015). In addition, they observed a significant effect of stroke rate, which varied between 30 and 36 strokes per minute, on the variability of the coordination between handle positions but not between the rowers' trunks. In a follow-up study in

which lower stroke rates were assessed, namely from 18 to 34 strokes per minute, crew coordination variability actually decreased with increasing stroke rate (Cuijpers et al., 2016). Apparently, the constraints introduced through the mechanical coupling changes the coordination dynamics defined across the rowers. Similarly, in a prehension task, it was shown that the degree to which dyads coordinated depended on whether the information available to them was visual only (Solnik, Reschechtko, Wu, Zatsiorsky, & Latash, 2015) or visual as well as proprioceptive and haptic (Solnik, Reschechtko, Wu, Zatsiorsky, & Latash, 2016). In fact, following their results, Solnik et al. (2016) concluded, “therefore, synergies quantified in tasks using visual feedback only may not be generalizable to more natural tasks” (p. 2267). Thus, how and via which medium dyads are coupled may affect the phenomena that can be eventually observed.

The issues raised here above indicate, as already voiced by several authors previously (cf. Lagarde, 2013; Richardson et al., 2015), that much can be gained by the dynamical approach to inter-person interaction by a further extension of the experimental agenda. Therefore, we here investigate a dyadic task that to a certain degree resembles the more ‘traditional’ coordination tasks but at the same time deviates from these in terms of two of the issues alluded to here-above, namely dyadic rope turning, as in rope jumping but without a jumper. In this task, two of the issues alluded to above play a role. First, task accomplishment is defined in terms of the rope movements rather than in terms of the coordination between the actors’ movements. The ‘quality’ of the rope rotations, which we define in terms of the relative phase variance between different points of the turning rope (see below), depends on but is distinct from the coordination between the two partners doing the turning. That is, the relative phase variance across different rope positions is not the same as that between the partners turning movements. Second, each partner may obtain information about task performance by observing the rotation of the rope (and maybe his/her partner’s movements), but also, and probably mostly so, via the hand-held rope, which transmits information about its behavior that can be perceived haptically. The coupling between partners is thus multimodal and potentially spans at least two time scales.

To investigate task performance we recorded the movements of five markers equidistantly attached to a rope. Next to the dyadic task performance, we also included an individual rope turning condition as a baseline performance. In the individual condition, one side of the rope was (quasi)fixed (see Section 2.3). We quantified the between-partner coordination and the rope rotation’s quality via the relative phase variance between both near-hand (i.e., the most outside) markers and across the middle and intermediate markers, respectively (see Fig. 1). In addition, we calculated the directionality index of the coupling, a measure indicating the direction and relative strength of the coupling between two coupled oscillators, here, between the two near-hand markers.

As said, rope turning resembles the ‘traditional’ social coordination paradigms but also deviates from them in certain ways that may affect the observable phenomena. Indeed, the focus on a performance variable associated with the rope rather than the coordination between agents per se excludes a conceptualization of the task in terms of standard coupled oscillators. Regardless, as the resemblance allows more easily for theoretically and experimentally based expectations than the deviations, our expectations were largely but not uniquely aligned with those derivable from paradigmatic (social) coordination studies. In the following, we focus on three issues. First, we examined differences and similarities between individual and dyadic task performances. In that regard, we expected the coordination between the outer near-hand markers as well as the rope rotation’s quality to be higher in the individual condition than in the dyadic condition, because we anticipated differences in spontaneous turning frequency, analogous to an oscillator’s eigen-frequency, between dyadic partners (detuning). In line with model predictions (Fuchs & Kelso, 1994; Schmidt, Shaw, & Turvey, 1993; Schmidt & Turvey, 1995), empirical studies have shown that when participants oscillate two pendulums with different eigen-frequencies, the patterns of coordination departed from intended  $0^\circ$  and  $180^\circ$  coordination, and that the pendulum with the higher eigen-frequency lead the one with the lower eigen-frequency. In addition, under such detuning the variability of the relative phase increased (Schmidt et al., 1993, 1998; Treffner & Turvey, 1995). These phenomena have been shown to be equally present in inter-person coordination (Amazeen, Schmidt, & Turvey, 1995; Schmidt et al., 1998). Second, we examined the effect of rope turning frequency on task performance. Although we did not systematically impose different turning frequencies, we anticipated

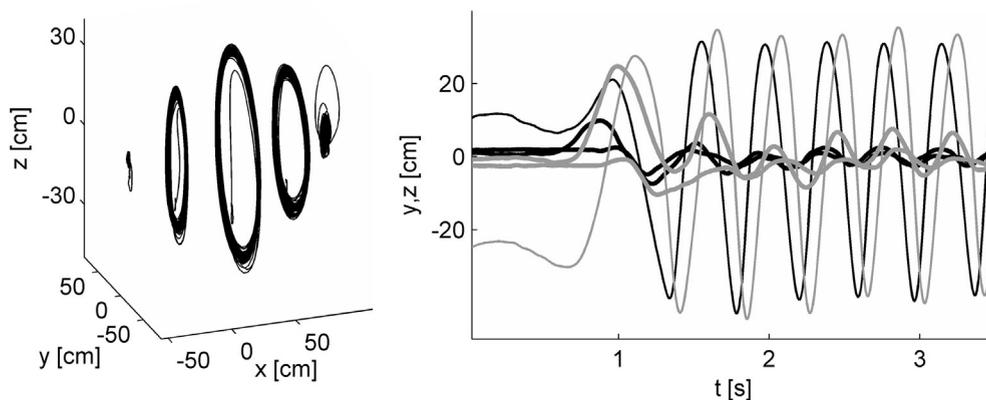


Fig. 1. Rope movements. The left panel depicts the rope movements corresponding to all five markers in three dimensions. The right panel depicts the rope movements corresponding to the near-hand markers (thick lines) and middle marker (thin lines) for the y and z-direction (black and gray lines, respectively) for the first few seconds.

that the participants, and pairs thereof, would adopt different turning frequencies. For both performance conditions (i.e., individual and dyadic), we expected turning frequency to correlate positively with the rope rotation's quality as the centrifugal force scales with turning frequency. Having said that, in both conditions the movements of the performer(s) will affect the quality of rope rotation, and faster movement execution is typically accompanied by increased variability, which, we presume, translates into reduced rope rotation's quality. That is, we envision that our expectation may have to be adjusted in view of competing tendencies affecting the rope rotations. Third, in an explorative fashion, we investigated whether and how the quality of the task performance, defined in terms of the rope turning quality, varied with various performance measures, and in particular, whether individual performances are predictive of the dyadic one.

## 2. Methods

### 2.1. Participants

Thirty-two young adults ( $24.2 \pm 2.5$  years) participated voluntarily in the study, 30 of which were right-handed and two of which were left-handed. The data pertaining to the left-handers will not be reported here. All participants had normal or corrected to normal vision and had no physical or neurological impairments. All participants provided a written informed consent prior to their participation. The study was conducted in accordance with the Declaration of Helsinki.

### 2.2. Apparatus

The turning rope was made of polyester (diameter: 5 mm; weight: 56 g) and had a plastic handle (24 g) at each end. The handle-to-handle length was 204 cm. Five reflecting spherical markers with a diameter of 20 mm each were attached to the rope equidistant of 50 cm. The two markers at the rope's endpoints were positioned at 2 cm from the plastic handles. The marker movements were recorded by a two-camera Elite 3D system (Elite Motion Analysis 3D System, BTS, Milan, Italy) at a sampling frequency of 100 Hz.

### 2.3. Procedure

The experiment consisted of two sessions. In the first session, each individual participant held one of the plastic handles and turned the rope individually (the individual condition). The experimenter immobilized the other side of the rope by holding the corresponding handle tight with both hands. Note that as the marker closest to the (quasi) immobilized handle was positioned at a distance of 2 cm, it revealed small amplitude oscillations in the individual condition, as the rope movements exerted some periodic force on the experimenter's hand that was striving to immobilize the handle. Observation of the experimental runs, however, indicated that such parasitic movements were minor, and are thus unlikely to have affected the reported results. Thirty participants performed the individual condition in which each participant performed five 15 s trials. In the second session two participants turned the rope together (the dyadic condition) where each participant held and turned one plastic lever. Combining 30 right-handed participants formed fifteen unique dyads (i.e., no participant took part in more than one dyad). Each dyad performed ten 20 s trials in this dyadic condition. In both sessions, the participants sat on a chair, and the hand-to-hand distance between participants (or experimenter) was controlled so as to be 1.83 m at the onset of each trial. In all conditions the participants were instructed to turn the rope regularly at a self-chosen frequency. No communication between the partners of the dyad, verbally, bodily or otherwise, was allowed in the dyadic condition.

### 2.4. Data analysis

The movement of the turned rope took predominantly place in the frontal plane spanned by the  $y$  and  $z$ -axis (see Fig. 1); we therefore restrained the analysis to these directions. Prior to the analysis proper, all the time series ( $2$  [directions]  $\times$   $5$  [markers] =  $15$ ) were low-pass filtered with a 4th order Butterworth filter with a cutoff frequency 12 Hz. The time series contained a transient and a stationary part, during which the rope attained and maintained a regular rotation, respectively. We identified the 'transition' between the transient and stationary part via a custom-made algorithm, whose performance was verified via visual inspection. For the remaining analysis, the transient part of the data was omitted.

#### 2.4.1. Rope turning frequency

The rope turning (or main) frequency was determined via spectral analysis on the  $y$  component of the middle marker (the frequency of the  $y$  and  $z$  component were always the same) from the moment of rope rotation stabilization onwards.

#### 2.4.2. Harmonics

The power at the main frequency was determined after normalizing the spectral densities to 1. We next determined the power at the first two super-harmonics relative to the power in the main frequency.

#### 2.4.3. Relative phase

In order to investigate the relative phasing and its variability between markers, we computed the (circular) mean and variance of the relative phase for the  $y$  and  $z$  direction using circular statistics (Mardia & Jupp, 2000) between all marker pairs.

### 2.4.4. Quality of the rope rotations

We quantified the rope turning quality as one minus the average of the relative phase variance for the two marker pairs including the middle and intermediate markers (i.e., [2,3] and [3,4]) in both main directions (i.e.,  $y$  and  $z$ ). Values close to one thus indicate little relative phase dispersion between the three middle markers on the rope.

### 2.4.5. Directionality index

Finally, we computed the coupling index between both near-hand markers (for both the  $y$  and  $z$ -direction) using the evolution map approach as detailed by Rosenblum, Cimponeriu, Bezerianos, Patzak, and Mrowka (2002). In short, for each marker the (unwrapped) Hilbert phase  $\theta_{1,5}(t)$  (i.e., for the outer near-hand marker 1 and 5; see also Fig. 1) was computed first, followed by the computation of an increments vector of the Hilbert phase with a time shifted version of itself,  $\Delta_{1,5} = \theta_{1,5}(t + \tau) - \theta_{1,5}(t)$ , where we used a time shift  $\tau$  of one rope turning period. These increments are a function of an unknown noisy map,  $F(\theta_{1,5}, \theta_{5,1})$ , which depends on the phases  $\theta_{1,5}$ . The dependencies of  $\Delta_{1,5}$  on  $\theta_{1,5}$  were retrieved by fitting the map  $F$  (least squared method) by a finite Fourier series,  $F = \sum_{m,l} A_{m,l} e^{im\theta_1 + il\theta_5}$ , where  $m, l = 1:3$ . The coefficients capturing the coupling between the two systems is then defined as  $c_{1,5}^2 = \int_0^{2\pi} (\frac{\partial F_{1,5}}{\partial \theta_{5,1}})^2 d\theta_1 d\theta_5$ . The directionality index is calculated as  $d^{(1,5)} = \frac{c_5 - c_1}{c_1 + c_5}$ . The index ranges from 1 for unidirectional coupling (1  $\rightarrow$  5) to  $-1$  for the inverse. The coupling is symmetrical (viz., bidirectional) for  $d^{(1,5)} = 0$ .

Differences between the individual and dyadic conditions were statistically assessed by means of Welch  $t$ -tests. Values that deviated by more than three standard deviations from the mean were considered as outliers, and were removed from the data prior to the statistical analysis.

## 3. Results

An example of the rope movement in the dyadic condition, represented by the markers' movements, is shown in Fig. 1.

### 3.1. Rope turning frequency

Spectral analysis on  $y$  and  $z$  component of the middle marker (from moment of rope stabilization onwards) showed that these components were always one-to-one frequency locked. The average turning frequency in the individual condition was 2.48 Hz ( $\pm 0.51$ ). In the dyadic condition, the average frequency was significantly higher (3.01 Hz  $\pm 0.43$ ;  $t(32.423) = -3.720, p < .01$ ). Furthermore, in nine out of 15 dyads the average dyadic rope turning frequency was faster than the faster of the two partners' (average) individual turning frequencies. In the other six dyads, the average dyadic rope turning frequency fell in between the two partners' average individual turning rope frequencies. Regardless, the correlation between the detuning between partners (i.e., the difference between their spontaneous individual turning frequencies) and the change in frequency in the dyadic condition relative to the individual one was significant ( $p < .001$ ) and positive ( $r = .62$ ), indicating that the faster one's partner, the more the frequency in the dyadic condition relative to the individual one increased. Thus, while there was no systematic frequency adjustment towards the average of the spontaneous frequencies of the dyadic partners, there was a frequency adaptation between the partners' (individual) spontaneous frequencies in the dyadic condition.

### 3.2. Harmonics

We averaged the extracted harmonics in the  $y$  and  $z$  direction, and (separately) averaged those pertaining to both near-hand markers and the three middle markers. For the first harmonic, more power was contained in the middle three markers ( $\sim 12\%$  of the total power) than in the near-hand markers ( $\sim 8\text{--}10\%$  of the total power; see Fig. 2). Significantly more power was contained in the near-hand markers in the individual than in the dyadic condition,  $t(21.93) = 3.735, p < .005$ . The amount of power in the middle

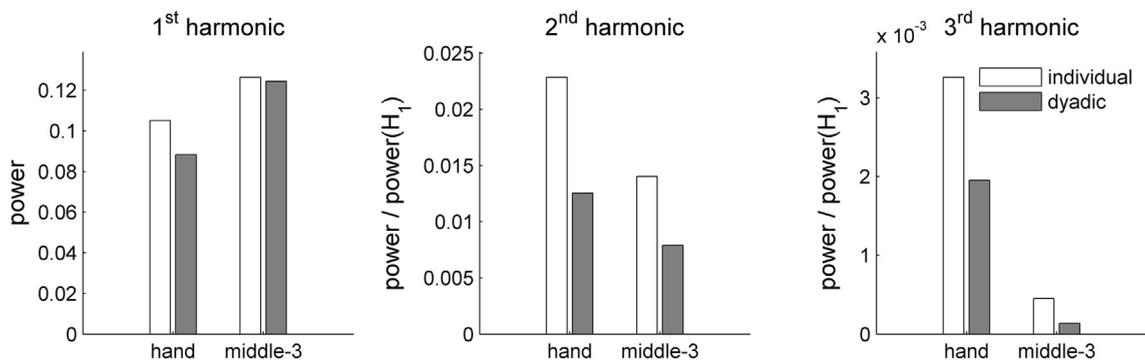


Fig. 2. Spectral power. Spectral power in the first, second, and third harmonic (left to right panel, respectively) for the near-hand and middle three markers and both conditions. The white versus gray bars correspond to the individual and dyadic condition, respectively. The power contained in the first harmonic is normalized relative to the total power in the spectral density estimate, while that in the second and third harmonic is normalized relative to the first harmonic.

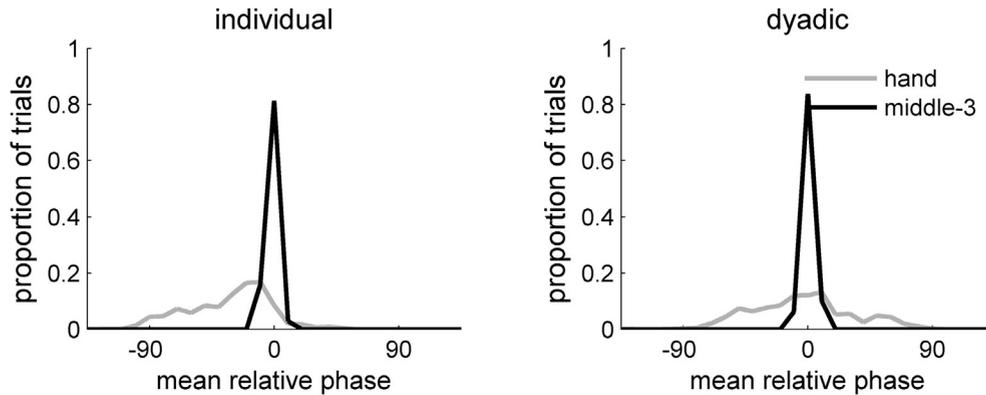


Fig. 3. Mean relative phase and relative phase variance. Frequency distributions of the mean relative phase across marker pairs including a near-hand marker and across pairs among the three middle markers in the individual and dyadic condition (left and right panel, respectively). The mean relative phase between the three middle markers is always small and falls within a limited range around  $0^\circ$  (with a slight offset for the individual condition). In contrast, the mean relative phase between pairs including a near-hand marker shows considerable spread in both conditions.

three markers did not differ significantly across conditions ( $p > .05$ ). The amount of power relative to the first harmonic was typically smaller for the 2nd than for the 3rd harmonic, and for both harmonics, smaller for the middle three markers than for the near-hand markers. The comparison between the individual and dyadic condition indicated that for the near-hand markers as well as for the middle markers the (relative) amount of power in the 2nd and 3rd harmonic was significantly higher in the individual condition than in the dyadic condition ( $t(41.47) = 4.507, p < .001$  versus  $t(42.98) = 3.912, p < .001$  for the near-hand and middle markers for the 2nd harmonic, respectively, and  $t(43.00) = 2.536, p < .05$  versus  $t(33.80) = 2.493, p < .05$  for the near-hand and middle markers for the 3rd harmonic). Thus, taken together, the middle three markers moved very harmonically while the near-hand markers showed some deviation therefrom, especially in the dyadic condition.

### 3.3. Relative phase

Fig. 3 depicts the frequency distribution of the trials' mean relative phases between marker pairs including a near-hand marker versus pairs among the three middle markers for both conditions. Note, a phase lag between marker  $i$  and  $j$  (i.e., a negative mean relative phase) indicates that marker  $i$  lags marker  $j$ . As can be seen, the mean relative phase across the middle three markers was confined to small values just below or centered around  $0^\circ$  for the individual and dyadic conditions, respectively. In contrast, the mean relative phase between the near-hand markers revealed a large spread between about  $-90^\circ$  and  $0^\circ$  and from  $-90^\circ$  to  $90^\circ$  in the individual and dyadic condition, respectively. Thus, considerable variation in between near-hand marker coordination is compatible with successful rope turning but appears to be damped out across the middle part of the rope.

The relative phase variance (averaged across the  $y$ - and  $z$ -direction) between the near-hand markers was significantly lower in the individual condition than in the dyadic one,  $t(18.40) = -2.675, p < .05$ . In contrast, across the three middle markers it was significantly higher in the individual condition than in the dyadic condition,  $t(34.60) = 4.116, p < .001$ . That is, while the coordination<sup>2</sup> between near-hand markers is more variable in the dyadic condition than in the individual one, that between the middle three markers is less variable in the dyadic condition.

### 3.4. Directionality index

Recall, the directionality index is a measure of the relative strength of the coupling between two oscillatory systems. That is, it is a measure of which of the two systems is more influenced by the other. A positive value indicates that the near-hand marker 5 (i.e., the actively turned one in the individual condition) had a stronger influence on near-hand marker 1 (i.e., the marker near the quasi-immobilized handle in the individual condition) than the reverse. Similarly, for the dyadic condition, a positive value indicates that the participant turning near-hand marker 5 had a stronger influence on the participant turning near-hand marker 1 than the reverse. The means of the directionality index in the individual and dyadic condition were not significantly different (mean  $\pm$  SD =  $0.09 \pm 0.30$  and  $0.08 \pm 0.28$ , respectively,  $p > .05$ ). In addition, while their distributions at first sight appeared different (not shown), a Kolmogorov-Smirnov test (MatlabR2013a) did not reach significance, indicating that the corresponding distribution were not statistically different.

<sup>2</sup> The relative phase variability quantifies the degree at which two moving elements relate to each other. For the individual condition, it reflects the degree of similarity between the participant's hand movements and the thereby induced oscillations at the other markers on the rope. Strong locking in this condition thus indicates that the participant's movements were consistent over time with little variation. While it is a signature of coordination, understood as the existence of temporal relations due to functional adjustments between moving elements, in the dyadic condition, by construction, they are not in the individual condition. This distinction should be kept in mind when we use the term "coordination" when comparing the individual and dyadic condition, which we sometimes do for reasons of communicative efficiency.

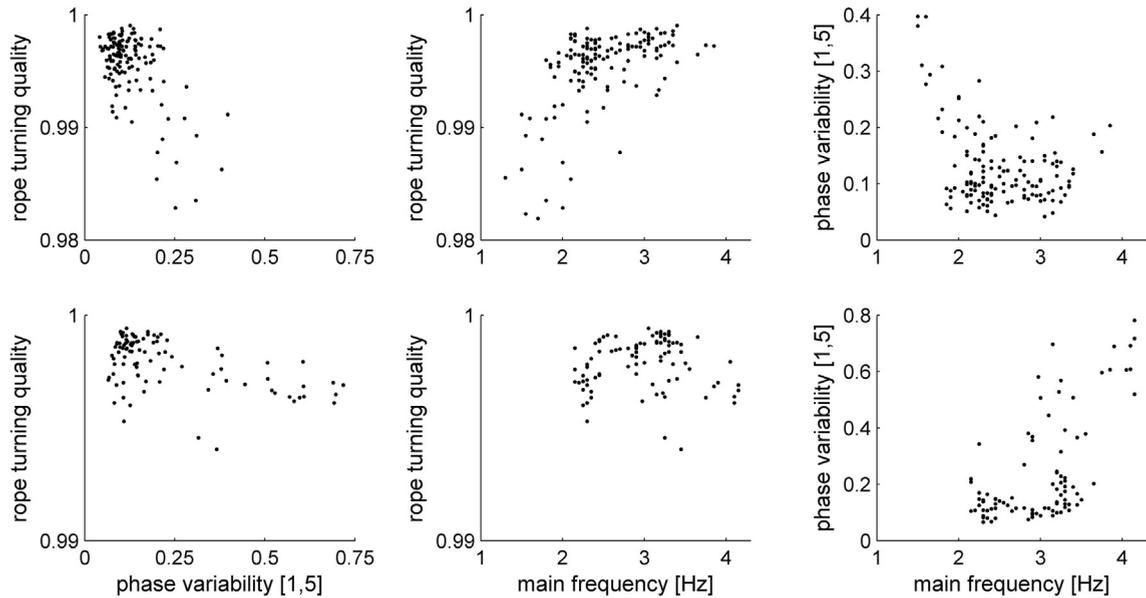


Fig. 4. Relations among performance variables for the individual condition (upper row) and dyadic condition (lower row). The left and middle panels show how the rope turning quality varies with the between-hand relative phase variance and turning frequency, respectively. The left panels depict the relation between turning frequency and the between-hand relative phase variability. Note that the scaling on all abscissas as well as on the ordinates in the left (but not middle and right) panel is identical.

### 3.5. Correlation analysis

#### 3.5.1. Correlations between near-hand markers and rope turning quality

We expected that a high degree of coordination between the near-hand markers would be associated with regular rope rotations. To investigate that expectation, as said, we quantified the rope turning quality as 1 minus the average relative phase variance for the two marker pairs including the middle and intermediate markers (i.e., [2,3] and [3,4]) in both main directions (i.e.,  $y$  and  $z$ ). The degree of coordination between the near-hand markers was quantified via the relative phase variance between both near-hand markers (i.e., 1 and 5) averaged across both directions. For both the individual and dyadic conditions, the Pearson correlation between the degree of near-hand marker coordination and rope turning quality were highly significant (both  $p < .001$ ) and moderate to strong,  $r = -.55$  (Fig. 4, upper left panel) and  $r = -.51$  (Fig. 4, lower left panel) for the individual and dyadic condition, respectively. Thus, the stronger the coordination between the near-hand markers (i.e., low relative phase variance), the better the rope turning quality.

#### 3.5.2. Correlations between turning frequency and performance variables

The correlation between the rope turning frequency and the turning quality was positive and significant in the individual condition ( $r = .54$ ,  $p < .001$ ; Fig. 4 upper middle panel). In the dyadic condition, however, the correlation was not significant ( $p > .05$ ; Fig. 4 upper middle right panel). Further, the correlation between the rope turning frequency and the coordination between near-hand markers (i.e., the relative phase variance between marker 1 and 5) was significant in both conditions (both  $p < .001$ ) but negative in the individual condition ( $r = -.30$ ) while positive in the dyadic condition ( $r = .55$ ; Fig. 4 upper and lower left panels, respectively). In sum, the rope turning quality scaled with the turning frequency in the individual but not in the dyadic condition, and more stable versus less stable between-hand coordination went hand in hand with faster rope turning in the individual and dyadic condition, respectively.

#### 3.5.3. Correlations between the directionality index and performance variables

In order to investigate whether the coupling direction (and strength thereof) affected the relative phasing between near-hand markers, we correlated the directionality index with the mean phase lag between the near-hand markers [1,5] in the  $y$  and  $z$ -direction. For the individual condition, the correlation with the phase lag in the  $y$ -direction as well as in the  $z$ -direction were negative and significant,  $r = -.62$  and  $r = -.57$ , respectively (both  $ps < .001$ ; Fig. 5, upper left and middle panel). Thus, the stronger the turned near-hand marker [5] was coupled to the fixed near-hand marker [1] rather than the inverse, the more the former led the latter. For the dyadic condition, both correlations were negative but significance was reached only for the  $z$ -direction ( $p < .001$ ;  $r = -.49$ ; Fig. 5, lower left and middle panel).

We additionally examined whether the directionality index correlated with the rope turning quality. For the individual condition, the correlation was significant ( $p < .001$ ) and positive,  $r = .47$  (Fig. 5, upper right panel), which indicates that the more the turned marker [5] influenced the fixed one [1], the better the performance. This relation seemed to be largely due to trials in which the

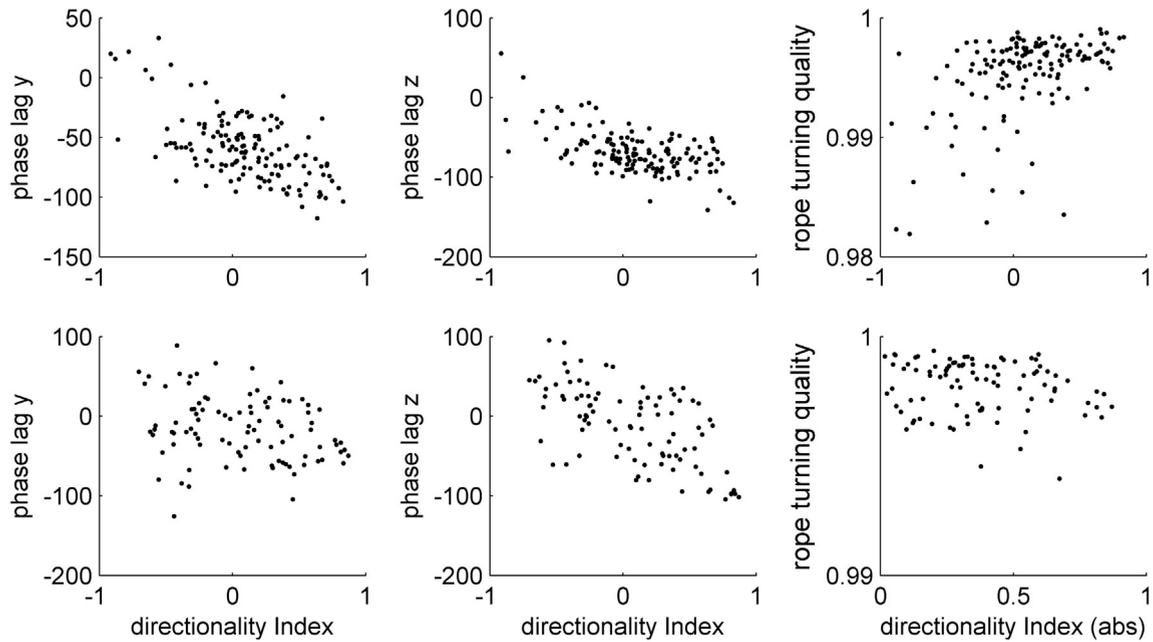


Fig. 5. The phase lag between near-hand markers in the y- and z-direction and performance as a function of the directionality index (left, middle and right columns) for the individual condition (upper row) and dyadic condition (lower row). Note that the lower right panel depicts the absolute value of the directionality index (see text).

directionality index was negative, however (Fig. 5). For the dyadic condition, we investigated whether the (degree of) coupling asymmetry between the partners of the dyads correlated with performance. We therefore took the absolute value as the directionality index as the direction of the coupling is irrelevant in this case. We found that the absolute directionality index correlated marginally but significantly with performance ( $p < .05$ ,  $r = -.21$ ; Fig. 5, lower right panel). The figure, however, suggested that the correlation was due to a few trials only, in particular those with an absolute directionality larger than about 0.5. Therefore, we further investigated the relation between the directionality index and performance. For the individual and dyadic condition, respectively, we tested for each individual and dyad whether the directionality index across trials was significantly different from zero. For the individual condition, this was the case for eight out of 30 participants; for two of these eight participants, the mean directionality index was negative (mean =  $-.59$ ), for the other six it was positive (mean =  $.49$ ). A  $t$ -test indicated that the performance of the eight participants was not significantly different from those for whom the directionality index was not significantly different from zero. When excluding the two participants with negative directionality, the  $t$ -test approached significance ( $p = .0616$ ). Interestingly, the rope turning quality of the two participants with negative directionality was markedly lower (i.e., the variability was higher; mean =  $.986$ ) than those for which it was positive (mean =  $.996$ ). In addition, their corresponding coordination between the fixed and ‘active’ marker was lower (mean =  $.431$  versus mean =  $.115$  for the relative phase variance between both markers for the two and six participants, respectively). While acknowledging the fact that statistical results between the two groups due to the few participants should be taken with caution, the three latter comparisons were all significant (both  $p < .001$ ).

In combination, these results suggest that whereas a positive directionality index has little, or at best, a marginally positive influence on performance, a negative directionality index, indicative of the passive near-hand marker 1 having more influence on the actively turned marker 5 rather than the inverse, is detrimental for performance. For the dyadic condition, the directionality index of six out of 15 dyads was significantly different from zero across trials. None of the  $t$ -tests between the performance variables (the quality of rope turning and both measures of the coordination between near-hand markers) of these groups was significant. In combination with the weak correlation reported above, these results indicate that the degree of coupling asymmetry between dyadic partners had only a marginal effect on the dyadic rope turning quality.

#### 3.5.4. Correlations between dyadic differences and dyadic performance variables

In the individual condition, we had established the participants’ spontaneous turning frequency, analogous to an oscillator’s eigen-frequency. In order to examine if differences in spontaneous frequencies (i.e., detuning) between two participants of a dyad influenced their rope turning performance, we computed the correlation between the (signed) detuning and the mean phase lags between both near-hand markers in the y and z-direction. We further computed the correlation between the absolute detuning and the relative phase variance between both near-hand markers as well as with the rope turning quality. None of these correlations turned out to be significant (all  $p > .05$ ).

In addition, we investigated whether the directionality index as observed in the individual condition was predictive of the performance in the dyadic condition. Thereto, we calculated the difference in directionality index between dyadic partners from the individual conditions and correlated it with rope turning quality in the dyadic performance. This correlation was not significant.

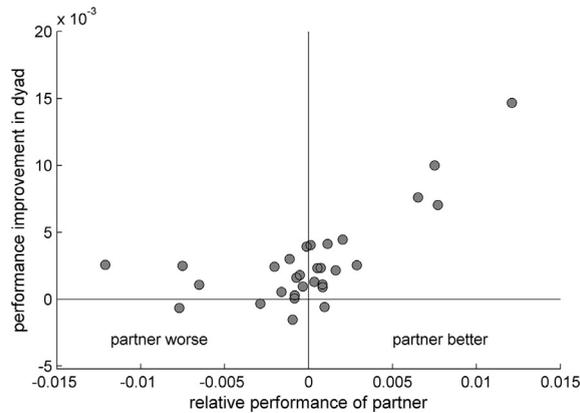


Fig. 6. The performance improvement in the dyadic condition (relative to the individual one) as a function of the relative performance of a participant relative to his/her partner in the individual condition.

Lastly, we examined whether the performance improvement (i.e., rope turning quality) in the dyadic condition relative to the individual condition depended on the performance of one partner relative to that of the other in the individual condition. As can be seen in Fig. 6, performance usually improved in the dyadic condition relative to the individual one. The performance improvement only scaled with the degree to which a participant was better than his/her partner when the latter outperformed the former in the individual condition.

#### 4. Discussion

We studied individual as well as dyadic rope turning performance in terms of the coordination between near-hand markers, which we assume to reflect the participant's action on the rope, the quality of the rope rotations as well as the directionality of the coupling between near-hand markers. We aimed, in particular, to compare the individual and dyadic task performance and further to explore the effect of rope turning frequency on task performance, and investigated if and how individual performances are predictive of dyadic performance. That is, we tried to find indications in the performances in the individual conditions as to why some dyads perform better than others. Below, we discuss our findings pertaining to these different aspects of rope turning and how they relate to previous findings and insights stemming from social coordination studies. However, since, to our best knowledge, there is no description of rope turning performance in the human movement science literature, we first briefly discuss our findings in that regard.

##### 4.1. Rope tuning performance

Rope turning performances in the individual and dyadic condition were largely similar. For both performances, most of the spectral power was by far contained in the main frequency; the first and second harmonic contained on average less than 2% of the spectral power in the main frequency. Deviations from harmonicity were more pronounced and common in the near-hand markers than in the three middle ones. In addition, the relative phase variance indicated that the coordination among the three middle markers was stronger than that between the near-hand markers. Thus, a typical rope turning performance is very harmonic and uniform. For both the individual and dyadic performances, stronger phase locking between the near-hand markers was associated with less variable rope rotations (i.e., better performance). This suggests that, as was expected, a smooth and regular insertion of energy in making the rope rotate translates into smooth and regular rope rotations. Nonetheless, successful rope turning appeared also possible with considerable relative phase lags and variability between the near-hand markers.

In that regard, we found that the directionality index correlated negatively with the mean relative phase between near-hand markers in both task conditions (although only so for the  $z$ -direction in the dyadic condition). This result indicates that the degree and direction of the coupling between the near-hand markers influence the mean relative phase between them, such that the more the turned marker [5] affects the fixed one [1], the more the former [5] leads the latter [1]. This observation mimics that in bimanual coordination where the more strongly affected non-dominant limb typically lags the dominant limb (de Poel, Peper, Lieke, & Beek, 2007).

In sum, even though a typical rope turning performance is harmonic and uniform, there are many quantitatively different coordinative solutions to the task, and the variability from the rope's endpoints towards the middle appears to damp out to a considerable degree. The latter is in all likelihood mainly due to material stress and friction within the rope leading to the dissipation of energy.

##### 4.2. Individual versus dyadic rope turning performance

In the individual condition, the experimenter tried to immobilize one of the rope's endpoints. As we made no recordings of the

experimenter's hand, we cannot rule out that the rope movements affected it. Any such effect, however, would most likely be a minor dampening of the rope movements. At any rate, the observations from the other experimenters indicated that the hand movements of the experimenter mobilizing the handle were negligible. We are therefore confident that any such minor parasitic movements have not substantially affected our reported results.

Anyway, the dyadic performances were better than the individual ones in terms of the regularity of the rope rotations (the task goal) captured by the relative phase variance across the three middle markers. In contrast, the coordination between the near-hand markers was weaker in the dyadic than in the individual performances. Recall, the correlation between the near-hand markers relative phase variance and the rope turning quality indicated that a stronger coordination between near-hand markers was associated with increased rope rotation regularity. From these correlations, and the fact that there was a stronger between near-hand phase locking in the individual condition than in the dyadic one, one would predict that performance in the individual condition would be better than that in the dyadic condition. As said, this was not the case. These observations thus suggest that the weaker coordination in the dyadic performances reflect adjustments of one or both of the dyadic partners to the ongoing rope rotations, and thus the partner's movements, and that the adjustments were functional rather than disruptive in the sense of improving the regularity of the rope rotations. In all fairness, however, rigorously testing whether and to what degree both partners contribute to the enhanced stabilization of the rope movements calls for a perturbation study (cf. Peper, Stins, & de Poel, 2013).

The improvement in rope turning quality was not equal for all participants. Interestingly, it was mostly present for participants who in the dyad were matched with a partner who performed better in the individual condition than the participant, and the improvement scaled with the degree in which the partner was better in the individual condition (if indeed the partner individually performed better; Fig. 6). The relation between the relative improvement in the dyads and the performance quality of one partner relative to other mimicked the one observed by Ganesh et al. (2015; cf. Fig. 1B). In that study, participants tracked moving stimuli either alone or in a dyadic condition in which, unbeknownst to the participants, both partners' tracking movements were physically coupled through a virtual compliant elastic band. As in the present study, dyadic performance improved relative to the individual one, on average even when a participant was coupled with a weaker partner, although the performance improvement in such cases was moderate only. That is, even when coupled with a weaker partner, the effect of being coupled bi-directionally to an active partner in the dyadic condition most often led to performance improvement, albeit only moderately. Being coupled to a better partner, however, led to larger performance gain. In combination, these results suggest that 'two are better than one' when the dyadic task allows for more information transfer than the individual one (bi-directional versus unidirectional<sup>3</sup> coupling), and indicate that being paired to a better performer increases one's own performance more so than when being paired with a weaker partner.

Due to the lack of an active bi-directional coupling between active performers in the individual condition, the present rope turning task cannot be trivially linked to the intra- versus interpersonal coordination comparison in which the coupling is always bi-directional between two actively moving units (Richardson et al., 2008; Schmidt et al., 1998). This latter comparison indicates that interpersonal coordination is weaker than intra-personal coordination, which is thought to be due to the visual coupling that is operative in interpersonal coordination being weaker than the neuromuscular coupling that is operative in intrapersonal coordination. In the present study, the coupling was presumably dominantly haptic/kinesthetic but also visual and mechanical in both performance conditions. Further, in both conditions it was bi-directional. The conditions were different, however, in that in the dyadic condition each partner coupled to the partner's movements whereas in the individual condition, if a participant's movements were affected by the low amplitude rope motions at the quasi-immobilized marker, then this was effectively a coupling to the effects of his/her own rope turning movements. We found that for the individual performance the directionality and strength of the coupling between near-hand markers correlated with the rope turning quality. Further investigation of this relation indicated that a stronger coupling from the quasi-fixed to the actively turned marker, rather than the reverse, was associated with performance deterioration whereas the inverse hardly affected performance, if at all. That is, the quality of the rope turning suffered when participants adjusted their movements markedly to those at the 'passive' quasi-fixed marker. This is likely so because in this situation it would imply adapting to motions that are the resultant of task performance but that do not contribute to its maintenance.

For the dyadic performance, we found absolute directionality indices to be approximately evenly distributed between 0 and 1, that is, from symmetrical to asymmetrical couplings (see Fig. 5). The absolute value of the directionality index between near-hand markers correlated marginally but significantly with the performance quality, such that smaller absolute directionality indices were associated with better performance rather than the reverse. However, when a posteriori separating the dyads into groups with across-trials zero versus non-zero directionality indices and comparing the performances of these groups, no significant differences were found. In combination, these results suggest that the degree of coupling asymmetry between partners of a dyad had only a marginal effect on performance at best, with larger asymmetries being detrimental to performance. Given that the a posteriori group sizes were relatively small (six and nine participants), however, this issue warrants further investigation.

In interpreting the directionality index, it should be noted that it provides a measure of relative coupling strength between two oscillating systems, and that the absolute degree to which two oscillators affect each other does not affect the index. The absolute degree to which two oscillators interact, however, does affect their coordinative stability. We therefore correlated the sum of the coefficients  $c_{1,2}$  from which the directionality index is derived (see Section 2), which is an estimate for the degree of overall coupling

<sup>3</sup> In fact, a particularity of the present study was that in the individual condition the coupling between the outer markers was also bi-directional (see Fig. 5 upper right panel), even though only one participant turned the rope. The bi-directionality suggests that the movements at the quasi-fixed marker induced by turning the rope in turn exerted some influence on the ongoing rope turning. At any rate, despite the bi-directionality, there were, by construction, no coordinative adaptations between participants in the individual condition.

between the oscillators, with the rope turning performance. This correlation was positive ( $r = .26$ ) and significant ( $p < .01$ ). Thus, while the degree of coupling asymmetry has a negligible to minimal effect on the turning quality, the absolute degree to which both dyadic partners were coupled scaled significantly with the quality of their turning performance.

In the literature, various degrees of coupling asymmetry have been reported. For instance, Peper et al. (2013) reported near symmetrical couplings between dyadic partners in inter-personal in-phase and anti-phase coordination. In that study, the coupling direction was assessed in a brief period following a mechanical perturbation of one of the partners' arm movements. The near symmetrical coupling indicated that both partners contributed about equally to re-establishing the pre-perturbation coordination pattern. Similarly, Richardson et al. (2015) reported weak but significant interpersonal coupling asymmetries in a dyadic rhythmic collision avoidance task. In that task, partners of dyads made rhythmic diagonal movements, and each partner's movements were orthogonal to those of the other. The dyads could avoid collision at midpoint by adopting a relative phase different from  $0^\circ$  and/or by making elliptical rather than straight movements. The participants that made the more elliptical movements were more affected by the ones making straighter movements than vice versa. Meerhoff, Rens, and De Poel (2014), however, found the interactions between partners in whole-body intentional in-phase to anti-phase mode switching to be mostly asymmetric. The latter two groups of authors suggested that the adoption of asymmetric 'leader – follower' strategies might enhance collective task achievement. Our present results were hardly supportive of that idea in suggesting that large asymmetries are detrimental to performance (albeit only moderately so). This difference across studies may well originate in the task constraints. Successful task performance in the Richardson et al. task required the adoption of an asymmetrical coordinative solution. In the task studied by Meerhoff and de Poel, the signal to switch came unexpectedly. Consequently, whichever agent switched first would adopt his/her movements less to those of the one switching latter rather than the inverse. In other words, asymmetrical solutions were introduced through the constraints operative in both these tasks. In contrast, in rope turning, similar to intentionally adopting specific coordination patterns (Peper et al.), successful task performance fares better with symmetrical coupling. That is, whether or not adopting asymmetrical roles is advantageous is in all likelihood determined by the task.

In sum, in dyadic performances both actors adjusted to each other, albeit to variable degrees, thereby improving the quality of the rope rotations. Performance gain in the dyadic condition relative to the individual one was observed mostly for individuals paired with individually better performers. Finally, while the degree of coupling (a)symmetry between the dyadic partners hardly, if at all, affected the rope rotations' quality, a stronger coupling between partners had a moderately positive effect thereon.

#### 4.3. Frequency adaptations between dyadic partners

We found clear indications that the partners in the dyadic condition adapted to each other in terms of the rope turning frequency. However, the dyadic turning frequency did not consistently fall within the range of both partner's individual turning frequencies but actually for 60% of all dyads was higher than that of either partner in the individual condition. That is, the dyadic turning frequency was not approximately halfway in between the two individual frequencies, as in standard detuned coupled oscillators, but was often higher than both individual spontaneous frequencies. This may be due to the fact that two individuals insert energy into the rope system in the dyadic condition rather than one only in the individual condition. At the end of the day, however, it is the periodic forcing that determines the rope's rotation frequency. Regardless, at the same time, we found a significant, positive correlation between the partners' detuning and the change in frequency in the dyadic condition relative to the individual condition, indicating that in the dyadic condition participants were affected by their partner's spontaneous frequency. This frequency attraction mimics the magnet-effect identified by von Holst (1908/1962) stipulating that two oscillators tend to pull each other to their preferred individual frequencies (see also Schmidt & O'Brien, 1997; Schmidt & Turvey, 1989), even though the dyads did not actually settle on a 'middle ground'. In combination, these findings suggest that the frequency attraction between two rhythmically moving units is generic, but that the task constraints dictate whether their coupled frequency will fall in between the individual ones or not.

#### 4.4. Rope turning quality does not deteriorate with turning frequency

In the individual condition, higher movement frequency was associated with a stronger phase locking between the near-hand markers as well as with better rope turning quality. This finding appears at first blush to stand in contrast to typical reports in the literature on inter-limb and inter-individual coordination, where higher movement speed is generally associated with increased performance variability (Kelso, 1995; Schmidt & Richardson, 2008). However, as pointed out above (see also Footnote 1), in the present individual condition the coordination between the near-hand markers is driven by a single person and is better interpreted as reflecting the consistency of the participant's movements than as a coordination. That is, it is more appropriate to compare the result in the individual condition with the literature on single limb movements. In that regard, it is well known that the variability between movement cycles or inter-tap intervals decreases with increasing movement frequency, as shown as early as 1886 by Stevens (in Vorberg & Wing, 1996; see also Dumas & Wing, 2007; Spencer & Zelaznik, 2003; and references therein). That is, from that perspective, our findings are in line with those commonly reported in the literature.

For the dyadic condition, the phase locking between near-hand markers decreased with increased turning frequency. That is, the coordination between the hand movements followed the well-known decrease in coordinative stability with movement frequency as often reported in the coordination literature—stability decreases at very low movement frequency have also been reported though (Schmidt et al., 1998; Zanone, Monno, Temprado, & Laurent, 2001). Apparently, the fact that the dyadic performers were coupled via a flexible medium did not alter this commonly observed relation. In contrast, the quality of the rope rotations, which we defined in terms of the relative phase variance among the middle markers, did not scale with the dyadic movement frequency in a clear manner.

At rope turning frequencies above about 3 to 3.5 Hz, however, the turning quality seemed to decrease mildly (Fig. 4, lower middle panel). The marked decrease in the between partner coordination for higher turning frequency thus only led to marginally more variable rope rotations, which may be partially explained in terms of the physical properties associated with the rope and the task of rotating it, namely the centrifugal force due to the rope's inertia, which scales quadratically with the rope's velocity. In addition, rope turning can be performed at multiple modes associated with different resonance frequencies. At the first mode, a single arc between both endpoints describes the rope rotation; at the second mode, two arcs, one up and one down, describe the rope rotation, etc. In the presented experiment, all participants turned the rope at the first mode, its fundamental frequency. At a sufficiently increased turning frequency, the rope motion would transit to its second mode. Prior to the stabilization of the second mode, however, the first one would lose stability, that is, the rope rotations would become less regular. The decrease in rope turning quality at the higher end of the observed dyadic turning frequencies may thus also reflect deviation from the resonance frequency. The experimental investigation of this hypothesis, however, requires that turning frequency be systematically scaled, which was not the case in the present study.

#### 4.5. Individual performance does not predict dyadic performance

In order to examine if and how individual performances and their differences between dyadic partners are predictive of the dyadic performance, we correlated several variables obtained in the different task conditions. The differences in individual preferred frequencies of dyadic pairs (i.e., the detuning) neither correlated with the phase lags between near-hand markers nor with the quality of the rope turning. This, at first blush surprising observation, appears to contrast empirical findings on intra-personal (Kelso, 1995; Schmidt et al., 1993) and inter-personal (Schmidt & Richardson, 2008) coordination. It should be noted, however, that in line with the dynamical model incorporating detuning, we defined it as the difference between the two spontaneous individual frequencies. However, as Sternad, Collins and Turvey have shown in a pair of studies (Collins, Sternad, & Turvey, 1996; Sternad, Collins, & Turvey, 1995), detuning is not accurately captured by this difference but should also take into account the ratio between uncoupled frequencies. A further explanation of this deviation must probably be sought in terms of the coupling between the dyadic partners, which in the present case was mediated by a flexible physical object, the rope, having its own dynamics. In typical social coordination studies, the coupling between two individuals is visual, and subjected to a short constant delay. In rope turning, individuals may also directly observe the other's movements, as well as that of the rope. In addition, and probably of most importance, the rope's movement provides both dyadic partners with kinesthetic and haptic information that likely involves a longer delay. Moreover, the rope only partially informs about the other partner's movement since its motion is a function of the movements of both partners. In other words, the coupling between both partners is mediated by a physical medium that damps out (see Section 4.1 above) the information flow between partners.

We further reported evidence that the coupling direction in the individual condition did not correlate with the coupling direction in the dyadic task. In addition, in the individual condition, for each dyadic partner we had obtained a directionality index. The differences in the individual partners' indices did not correlate with the rope turning quality in their dyadic performance. These findings suggest that who will be leaders versus followers in a dyadic setting cannot be reliably deduced from the individual performances, at least not in the present task context. In bimanual coordination, when studying intentional switches from in-phase to anti-phase coordination and vice versa, de Poel, Peper, and Beek (2006) found that the asymmetry in coupling strength between the non-dominant and dominant hand during transitions from in-phase to anti-phase was smaller than for transitions in the reverse direction. That is, the degree of coupling asymmetry between hands was dependent on the ongoing coordination pattern and not (solely) a 'fixed hardwired' feature. In a similar vein, our results suggest that the context within which a (social) coordination dynamics is assembled affects the (dominant) direction of the coupling between agents over and beyond the features that both agents bring to the common task.

While absolute individual performances were poor predictors of dyadic performances, we found that the relative difference between the dyadic partners' quality of performance (see also Ganesh et al., 2015) as well as the summed coupling indices had some predictive value for the dyadic performances. While consistent with Ganesh et al. (2015), our finding as regards the relative differences between partners is at odds with those of Bahrami et al. (2010) and Wahn, Schmitz, König, and Knoblich (2016), who reported that dyads benefitted when the partners individual performances were similar. In the study of Bahrami and colleagues, two dyadic partners made individual decisions in a low-level perpetual decision task and next communicated between each other to arrive at a joint decision. That is, simultaneous coordinated action did not underlie task performance. In the study of Wahn et al., the dyadic partners performed conjoint aiming movements in which each partner controlled one direction of the movement (vertical, horizontal). Whether or not the movements were coupled was not reported. It is thus unclear whether the presence or absence of coupling can explain the differences between the Bahrami and Wahn studies and ours. In both studies, however, and in contrast to that of ours and of Ganesh and colleagues, proprioceptive and haptic coupling were absent. Whether the coupling medium affects dyadic performance and, more generally, how task constraints affect how inter-individual differences affect dyadic performance, remain open and interesting questions. At any rate, our findings are compatible with the thesis that dyadic performance depends more on how the partners relate to each other than to their individual capacities only.

## 5. Conclusion

We studied individual and dyadic rope turning performances from a dynamical perspective. We reported evidence that the rope rotations in the dyadic performances were less variable than in the individual performances despite a larger relative phase variability

between the near-hand markers. We inferred that these between-partner coordinative fluctuations represent functional adaptation between the dyadic partners. Additional adaptation between partners was observed in terms of frequency adjustments. Functional adaptations are one hallmark feature of synergies, the other being a dimensionality compression (Riley, Richardson, Shockley, & Ramenzoni, 2011; Turvey, 1990). Although we did not explicitly report such a compression, the existence of correlations between the different markers readily indicates that task performance can in principle be reduced to a few components. In combination, these results suggest that dyadic rope turning can be conceptualized in terms of an interpersonal synergy, in which, by implication, control is an emergent property defined across the dyadic system that cannot be reduced to its constituting partners (Riley et al., 2011).

We found clear evidence that the degree of the partners' detuning correlated with the change in frequency in the dyadic condition relative to the individual performances. The common frequency, however, was often higher than that of the spontaneous individual frequencies. That is, the frequency attraction between oscillators is maintained even though the task constraints modify its observable effects. Consequently, the introduction of novel (social) coordination tasks, such as rope turning, may help delineate task-specific observables from truly generic (social) coordination phenomena.

Whereas we found evidence that the quality of the dyadic performance was related to the relative differences between the dyadic partners, we failed to find individual fingerprints predictive of dyadic performance. As said, this finding both mimics and deviates from previous reports. This discrepancy across studies in this regard may suggest that the task dictates which individuals make for successful or less successful social groups. Indeed, the understanding of which individual features and/or differences between them allow for the formation of successful groups, and if and how this interacts with the task context is likely to remain an open question for some time to come.

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