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Rowing together: Interpersonal coordination dynamics with and without mechanical coupling

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ABSTRACT

Although most research on interpersonal coordination focuses on perceptual forms of interaction, many interpersonal actions also involve interactions of mechanical nature. We examined the effect of mechanical coupling in a rowing task from a coupled oscillator perspective: 16 pairs of rowers rowed on ergometers that were physically connected through slides (mechanical coupling condition) or on separate ergometers (no mechanical coupling condition). They rowed in two patterns (in- and antiphase) and at two movement frequencies (20 and 30 strokes per minute). Seven out of sixteen pairs showed one or more coordinative breakdowns, which only occurred in the antiphase condition. The occurrence of these breakdowns was not affected by mechanical coupling, nor by movement frequency. For the other nine pairs, variability of steady state coordination was substantially lower in the mechanical coupling condition. Together, these results show that the increase in coupling strength through mechanical coupling stabilizes coordination, even more so for antiphase coordination.

1. Introduction

Coordinating our actions with others is a natural part of daily life. There is a tendency to synchronize, which is so powerful that individuals often entrain their movements even without being aware of doing so (e.g., Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007). For instance, when walking side-by-side with someone else, there is a natural tendency to fall in step (e.g., Van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008), and during conversation the mere connection through the rhythms in talk alone is sufficient for bodily synchronization to arise between individuals (Shockley, Santana, & Fowler, 2003). This indicates that as long as there is some form of interaction, or coupling, synchronization emerges between persons to some degree (e.g., Lagarde, 2013). In other forms of interpersonal interaction, synchronization is deliberately established, such as in crew rowing (De Poel, De Brouwer, & Cuijpers, 2016). A rowing crew moves in synchrony to achieve optimal performance: collective performance is defined by the behavior of the crew as a unit rather than the summed individual contributions of each rower (De Poel et al., 2016). Notably, rowers are not only perceptually coupled: an important source of interaction for the rowing crew is the mechanical link between the rowers through the boat. Whereas studies on interpersonal coordination dynamics have almost exclusively focused on perceptual coupling (e.g., seeing or hearing the movements of the other, see Schmidt & Richardson, 2008), the effects of mechanical coupling on interpersonal coordination are relatively unexplored (e.g. Harrison & Richardson, 2009; Marmelat & Delignieres, 2012). Here, we present results of an experimental lab study that examines the coordination between two rowers on ergometers when mechanical coupling is either present or absent.

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1.1. Coupled oscillator dynamics

Given the cyclical nature of the rowing stroke, we can consider a crew of rowers as a system of coupled oscillators (De Poel et al., 2016). In their seminal paper, Haken, Kelso, and Bunz (1985) modeled such coupled oscillators (in their HKB-model) to capture within-person synchronization processes as observed in Kelso (1984). Among other things, the HKB-model captures that coordinative stability for both in-phase and antiphase coordination decreases with an increase in movement frequency. At a certain frequency, the antiphase pattern becomes unstable, resulting in a transition to the stable in-phase pattern. As this transition is approached, critical fluctuations become apparent, reflected in an increase in variability of relative phase, which signifies the decrease in stability of the coordination pattern (Kelso, Scholz, & Schöner, 1986). In the HKB-model (and also in other coupled oscillator models, see e.g. Pikovsky, Rosenblum, & Kurths, 2001), the strength of the coupling reflects the degree to which the components that constitute the system influence each other. The model predicts that attractor strength (reflecting the stability of a pattern) increases with coupling strength (e.g., De Poel, 2016; Fuchs & Jirsa, 2008; Haken et al., 1985). Hence, theoretically, stronger coupling stabilizes coordination (Haken et al., 1985).

Importantly, it has been empirically shown that these coupled oscillator principles also apply to coordination beyond bimanual coordination, for instance sensori-motor coordination (e.g., Kelso, Fink, DeLaplain, & Carson, 2001; Wimmers, Beek, & Van Wieringen, 1992), coordination with a virtual partner (Dumas, De Guzman, Tognili, & Kelso, 2014; Dumas, Lefebvre, Zhang, Tognoli, & Kelso, 2018) and, important in the present context, interpersonal coordination (Richardson et al., 2007; Schmidt & Richardson, 2008; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990).

Previous laboratory experiments on crew rowing (Cuijpers, Zaal, & De Poel, 2015; De Brouwer, De Poel, & Hofmijster, 2013), in which rowers rowed on coupled ergometers,[1] confirmed that in-phase rowing was more stable than antiphase rowing. However, the results of Cuijpers et al. (2015) did not completely align with frequency-related predictions from coupled oscillator dynamics (Haken et al., 1985). That is to say, Cuijpers and colleagues tested whether an increase in movement frequency would result in a transition from antiphase to in-phase coordination. Dyads rowed in in-phase and antiphase coordination starting at 30 strokes per minute (*spm*) and increased their movement frequency every 30 *s* until they could not increase their movement frequency any further. The rowers were instructed to return to the intended pattern when they slipped into another pattern. In contrast with predictions from the HKB-model, increasing movement frequency did not yield transitions from antiphase into in-phase coordination (two transitions were observed, but these did occur already at the lower stroke rates of 30–33 *spm*). Moreover, for both patterns the variability in relative phase did not seem to change between stroke rates of 30 and 36 *spm*. These results led to the suggestion that the mechanical coupling may be such a strong form of coupling that it annihilates a frequency-related decrease in stability and the associated transitions from anti- to in-phase coordination. It seems worthwhile to test this head-on by investigating the stability of crew coordination over different tempos with and without mechanical coupling.

1.2. Coupling

As in crew rowing, many interpersonal tasks, such as jointly carrying and moving large objects (Lanini, Duburcq, Razavi, Le Goff, & Ijspeert, 2017), dance (Sofianidis, Elliott, Wing, & Hatzitaki, 2014), holding hands while walking (Roerdink, Van Ulzen, Niekel, Van den Eijkel, & De Poel, 2016; Sylos-Labini, d'Avella, Lacquaniti, & Ivanenko, 2018), or rope-skipping (Huys et al., 2018) also involve mechanical coupling in terms of physical interactions. Mechanical coupling (in crew rowing via the boat that the rowers share) may be considered as a substantial from of coupling because, there is no way to ‘escape’ from the direct physical interaction, as an agent/component gets passively moved due to forces applied by the other agent/component (Cuijpers et al., 2015). In crew rowing each rower pushes off against the boat (or the ergometer in a lab setting), which alters the movement of the boat, and thereby the movements of other crew members. In fact, even when a rower would not actively be moving, he/she will be moved passively by the forces his/her crew members apply to the boat. This is similar to the mechanical exchange in non-biological systems, such as two metronomes that are jointly placed on a movable base (Pantaleone, 2002)[2] or coupled pendulum clocks (Huygens, 1665; see Bennet, Schatz, Rockwood, & Wiesenfeld, 2002; Kapitaniaka, Czolczynskia, Perlikowskia, Stefanskia, & Kapitania, 2012; Pikovsky et al., 2001).

A study that did explore mechanical coupling in interpersonal coordination was the experiment by Harrison and Richardson (2009), in which they combined two walking participants into a quadrupedal system. They manipulated coupling both perceptually (using a blindfold) and mechanically (strapping participants together using a foam appendage). Without the explicit instruction to synchronize, patterns comparable to quadrupedal locomotion emerged when participants were coupled. However, the authors only reported which patterns occurred and how often they occurred, not how stable those patterns were. This means that the direct relation between mechanical coupling and the stability of interpersonal coordination was not reported.

A study on intentional (rather than spontaneous) mechanically coupled interpersonal coordination, was the experiment by Marmelat and Delignieres (2012). In their study, pairs of participants were instructed to swing pendulums in interpersonal in-phase synchrony, while coupling was manipulated by combining and isolating different sources of interaction between them: in the ‘weak

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[1] The ergometers are connected through slides allowing the ergometers to move with respect to the ground (to simulate the movements of the boat with respect through the water and to be connected to become one ‘boat’ - see “Experimental_Conditions.mp4”). Similar to on-water rowing, the rowers are connected to each other via the footplates that are fixed on the ergometers. The seats of the rowers can move independently from each other, as do the handles; these are connected to individual flywheels.

coupling' condition, participants wore earplugs and had only peripheral visual access to the other participant; in the 'intermediate coupling' condition participants had full access to visual and auditory information; and in the 'strong coupling' condition they additionally sat arm-in-arm to exchange haptic information. Note that by linking the arms together, participants are mechanically coupled. The authors showed that coordinative stability only improved in the intermediate- and strong coupling condition with respect to the weak coupling condition; no significant difference between the intermediate (no mechanical coupling) and strong (mechanical coupling) coupling condition was found.

Next to such pure mechanical exchange, the physical connection via the boat also implies that the rowers are able to *perceive* the forces. Previous lab studies that focused on effects of such haptic/kinesthetic interaction between persons showed that participants performed better on a targeting task when they were mechanically linked than when they performed the task individually (Reed et al., 2006). Moreover, participants pulling a pole back and forth between two targets at different movement frequencies and amplitudes tended to amplify their forces, especially for more challenging conditions (e.g., higher movement frequencies and smaller amplitudes; Van der Wel, Knoblich, & Sebanz, 2011). Such amplified force exchange seems even more apparent in expert than novice dancers (Sawers et al., 2017). Together, this suggests that physically interconnected persons use the haptic coupling as a communication channel (Reed et al., 2006; Sawers et al., 2017; Van der Wel et al., 2011). This principle may hold for crew rowing as well. For instance, Hill (2002) suggested that an increase in force produced via the oar(s) provides a better kinaesthetic perception, which facilitates the mutual adaption of force patterns. Together, for a rowing crew the mechanical (including the haptic/kinesthetic) coupling via the boat is considered to be a substantial from of coupling (Cuijpers et al., 2015).

1.3. Aim

The aim of this study is to test the effect of mechanical coupling on the stability of interpersonal coordination using a crew rowing task. Rowers rowed on ergometers that were connected through slides (mechanical coupling condition, or MC) or not (no mechanical coupling condition, or NMC). When the rowers are mechanically coupled, they set each other in motion and thus influence each other more substantially than when they are not mechanically coupled. Therefore, we expect that the mechanical coupling through the boat that the rowers share stabilizes interpersonal coordination.

As research on coordination dynamics further suggests that the stability of coordination is affected by pattern (in- or antiphase) and movement frequency (e.g., Kelso et al., 1986; Schmidt & Richardson, 2008), we asked participants to row in in- and antiphase at two different movement frequencies (20 and 30 *spm*). In line with the HKB-model, we expect in-phase to be more stable than antiphase coordination. Furthermore, although the HKB-model predicts that coordinative stability decreases with an increase in movement frequency, previous studies in crew rowing suggest no effect of increasing movement frequency (Cuijpers et al., 2015) or even an *in*crease of coordinative stability with increasing movement frequency (from 18 to 26 *spm*, see Cuijpers et al., 2017). By having our participants row in both patterns at two stroke rates, we aim to address this mismatch between the theoretical model (i.e. the HKB model, that covers many tested instances of interpersonal coordination) and previous empirical findings on crew rowing.

2. Method

2.1. Participants

Thirty-two rowers participated in the experiment (12 women, 20 men; age 22 ± 3 years; body height 1.85 ± 0.08 *m*; body mass 78 ± 10 *kg*; rowing experience 4 ± 3 years; training load 9 ± 5 h per week), who were paired into 16 combinations. All pairs signed up together as team mates. Only rowers with at least one year of experience in national competition were included. For more detailed information on the different combinations, see Table 1 in Supplementary Materials. Participants provided written informed consent. The local Ethics Committee approved the study that was conducted according to the principles expressed in the Declaration of Helsinki.

2.2. Experimental setup

Pairs rowed on two ergometers (Type E, Concept2, USA) placed behind each other. The ergometers were placed on slides in order to reflect the movement of the 'boat' with respect to the water (see Fig. 1). To manipulate mechanical coupling, the ergometers were either connected to each other (mechanical coupling condition or MC) through those slides (forming a mechanical linkage as if they are rowing in the same boat) or disconnected from each other (no mechanical coupling condition or NMC; see also Supplementary Materials "Experimental_Conditions.mp4".) Note that, regardless of whether the rowers are mechanically (and thus also haptically/kinaesthetically) coupled, the rowers are perceptually coupled in terms of visually (e.g., the stroke rower moving towards or away from the bow rower) and auditory (e.g., the roaring of the ergometer flywheels) coupling. The resistance of the ergometer flywheels was set at an aerobic constant of 1.20 $10^{-4} \cdot kg \cdot m^2$ (i.e., drag factor 120, e.g., Cuijpers et al., 2015; Den Hartigh, Marmelat, & Cox, 2018).

The kinematics of the rowers and ergometers were recorded with an Optotrak Motion Capture System (Northern Digital Inc., Canada) using 12 markers. As illustrated in Fig. 1, five markers were placed on the left side of each rower; on the wrist, hip (greater trochanter) and three on the shoulder. Two markers were placed on the ergometers. The markers' 3D trajectories were recorded at 150 *Hz* using four Optotrak cameras placed around the measurement volume.

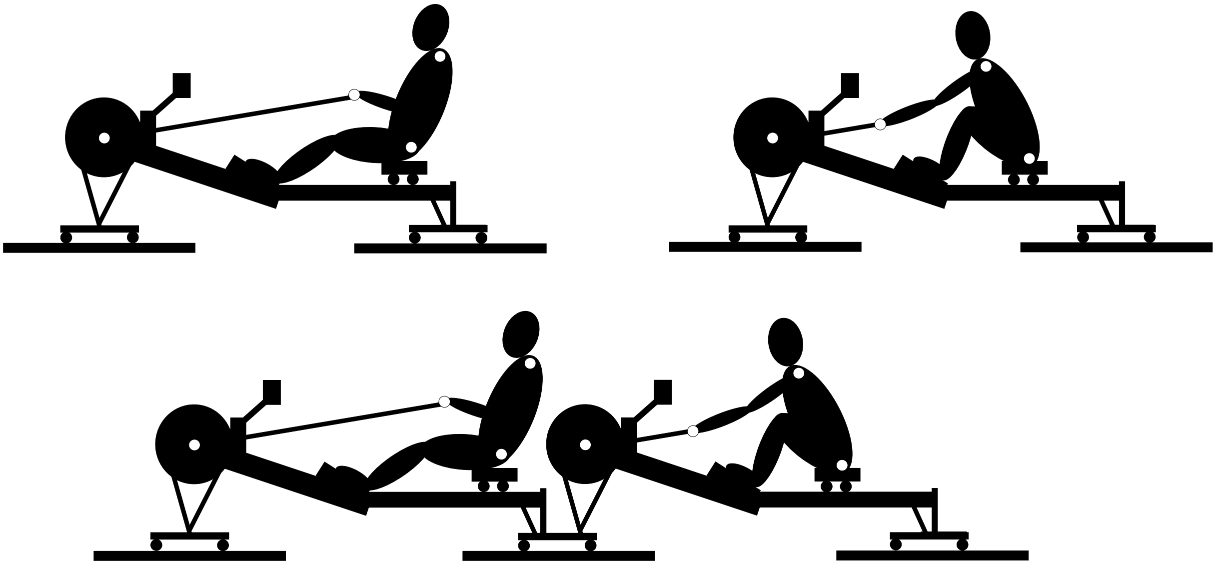

Fig. 1. Experimental setup. In the NMC condition (upper panel) rowers rowed on separate slides, whereas in the MC condition (lower panel) the ergometers were connected through the slides to move as one ‘boat’. Marker positions are indicated by white dots (the shoulder marker consisted of three markers).

2.3. Protocol

To warm up each participant rowed individually for 5 min. Next, a number of individual trials were administered to determine the individual force-profiles, and to investigate whether rowers alter their force-profiles when rowing with someone else. As the current study focuses on crew coordination, these individual trials were left out of the analysis. Subsequently, to get familiar with the experimental setup and the antiphase pattern, a pair rowed together for 5 min in in-phase and 5 min in antiphase coordination with 2 min of rest before each set of trials. Finally, pairs performed 2 sets (one with and one without mechanical coupling) of 4 counterbalanced trials: 2 patterns (in-phase and antiphase) performed and two tempos (20 and 30 *spm*). These sets consisted of 2 min trials with 2 min of rest between the trials. The stroke rower received real-time feedback about stroke rate on a monitor (PM4, Concept 2, USA). Similar to previous crew rowing experiments (Cuijpers et al., 2015; De Brouwer et al., 2013), rowers were instructed to return to the instructed pattern if they felt that they were slipping into another pattern.

2.4. Data analysis

Positions in the sagittal plane were analyzed using customized procedures in Matlab (MathWorks, USA). From the positional data two sets of two kinematic time series were calculated: 1) handle positions (based on the markers placed on the handles) relative to their ergometers; and 2) forward-backward Center of Mass (*CoM*) movement of both rowers (estimated as the mean position of hip and shoulder markers) with respect to their ergometers (i.e., with respect to the moving base). The time series were interpolated using a piecewise cubic smoothing spline and filtered using a bidirectional second order low-pass Butterworth filter with a 15 *Hz* cut-off frequency.

2.5. Relative phase

A discrete measure of relative phase based on point-estimates of handle and CoM extrema near the catch and finish was calculated for each full cycle as:

$$\phi_i(t) = \frac{t_{2,j} - t_{1,j}}{t_{2,j+1} - t_{2,j}} 360^\circ \tag{1}$$

These extrema of the signals were determined using a custom-made peak-picking algorithm. The catch is the start of the propulsive phase, where the blade enters the water/ when the handle is closest to the flywheel and the finish is the end of the propulsive phase, when the blade leaves the water/ the handle is farthest from the flywheel. We choose these instances as the catch and finish are clear and distinct points in the movement cycle which may be used as anchor point (Cuijpers et al., 2017).

This discrete measure of relative phase was determined because the rowing cycle deviates from perfect harmonicity as it consist of two clear halves, namely the ‘drive’ (i.e., propulsive part of the stroke) and ‘recover’ (i.e., part of the stroke where the rowers return to their catch-position), which differ in duration (Cuijpers et al., 2015; De Brouwer et al., 2013; Martin & Bernfield, 1980). As deviations from within-cycle harmonicity may introduce artefacts in the calculation of continuous relative phase, we opted for a discrete measure of relative phase that is not sensitive to such deviations from harmonicity.

2.6. Dependent measures

For all trials, deviations from steady state, ‘Coordinative breakdowns’, defined as a deviation of relative phase value $\geq 180^\circ$ of the instructed pattern for at least one movement full cycle, were counted. Note that such ‘breakdowns’ are associated to the concept of ‘transitions’. In most coordination dynamics studies the term ‘transition’ indicates a clean change from an anti- to an in-phase pattern, after which participants (as instructed) do not return to the initial pattern. That is to say, for such a definite change to occur, it is critical that the participants are instructed to “not resist if they would feel they would slip into another pattern” (e.g., see Kelso, 1984, 1995; Schmidt et al., 1990). In contrast, in the current study, we instructed participants to return to the instructed pattern if they were slipping out of the instructed pattern. This means that the ‘transitions’ that occurred in the present study resulted in a temporary change of the antiphase pattern, after which the rowers tried to restore their antiphase coordination. Therefore, to avoid confusion, for the remainder of the article, we decided to not use the term ‘transition’ but to quantify short deviations from the instructed pattern as ‘coordinative breakdowns’.

Next, for the steady state trials (in which no coordinative breakdown occurred), the time series were analyzed over steady state bins (30 *cycles*) for each condition. Based on the handle time series, for each condition standard deviations (*SD*) of discrete relative phase ($SD\phi_{catch}$ and $SD\phi_{finish}$) were calculated as measures of coordinative stability.

2.7. Statistical analysis

To investigate the effect of coupling and stroke rate on the occurrence of coordinative breakdowns, a Chi-square test was performed. Next, for the pairs that showed steady state coordination (i.e. no coordinative breakdowns), each of the above-mentioned dependent measures was subjected to a 2 (Coupling: NMC vs. MC) × 2 (Pattern: in- vs. antiphase) × 2 (Tempo: 20 vs. 30 *spm*) repeated-measures ANOVA. Pairs that showed coordinative breakdowns were left out of the latter analyses, as this would distort the results. An α of 0.05 was adopted for all tests of significance. Interaction-effects were further analyzed via post-hoc Bonferroni-corrected paired-samples t-tests.

3. Results

3.1. Coordinative breakdowns

All pairs were able to perform the two instructed stroke rates. Seven out of the 16 pairs showed a total of eleven coordinative breakdowns. These only occurred in antiphase coordination; no breakdowns from in- to antiphase rowing took place. An example of a breakdown is depicted in Fig. 2 and in the Supplementary materials “Breakdown.mp4” (the first breakdown shown in the footage is depicted in Fig. 2). As can be seen from both Fig. 2 and the footage, the pairs are able to restore coordination within the next cycle. In the NMC condition coupling condition 7 breakdowns occurred: 3 at 20 *spm* and 4 at 30 *spm*. In the MC condition 4 breakdowns occurred: 3 at 20 *spm* and 1 at 30 *spm*. A Chi-squared test performed over the occurrences of antiphase breakdowns revealed no significant differences for Coupling nor Tempo.

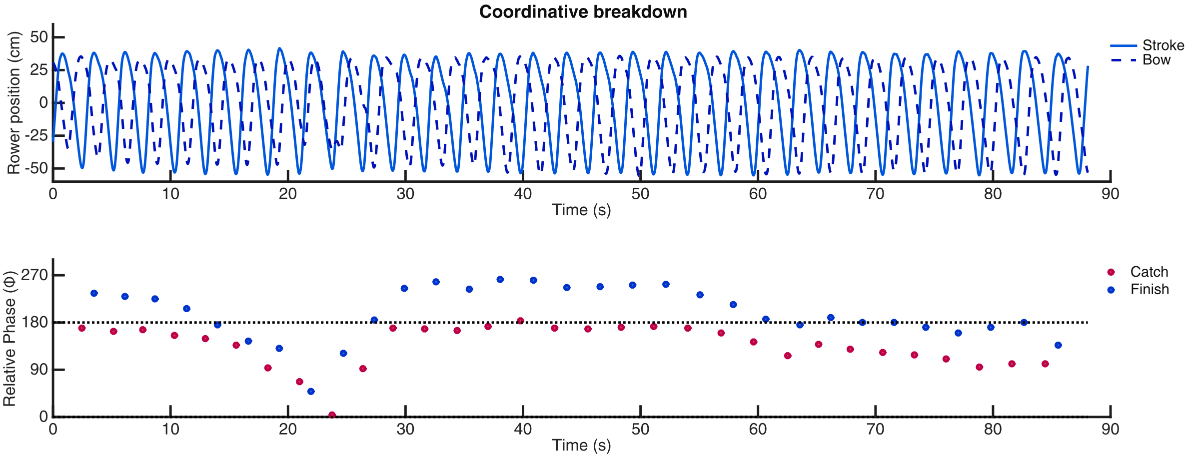

Fig. 2. Example of a coordinative breakdown. The upper panel shows the position of the stroke (solid line) and bow (dashed line), the middle panel shows the position of the ergometer system and the lower panel depicts the discrete relative phase for both catch (grey dots) and finish (black dots).

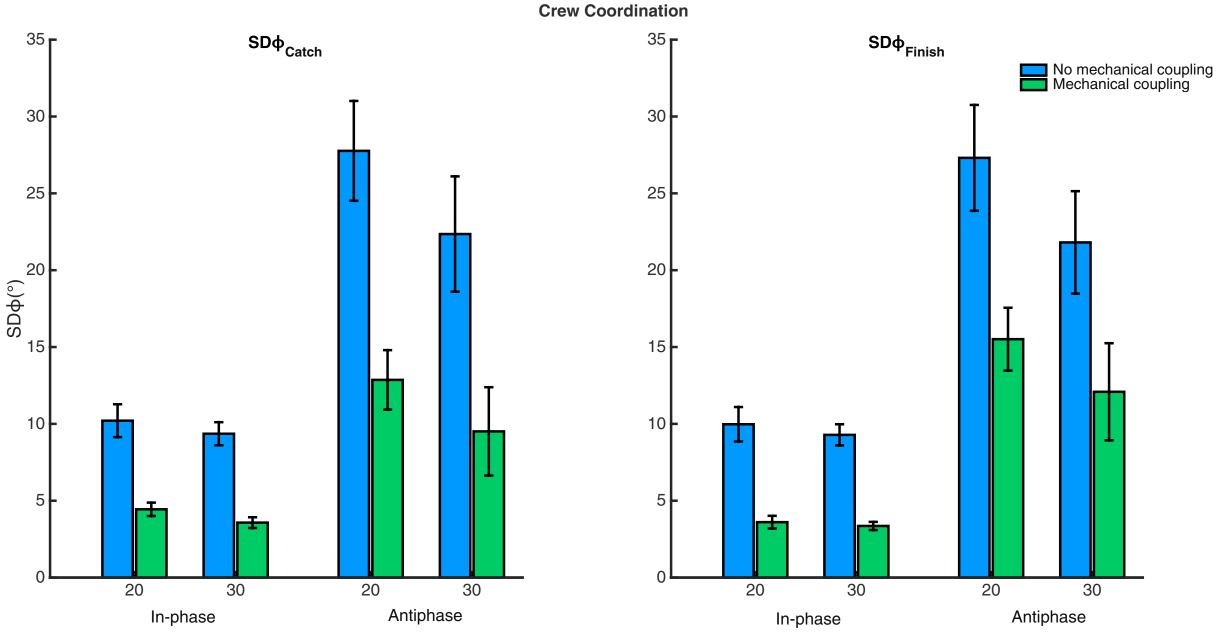

Fig. 3. Variability of relative phase over the complete cycle (SDϕ$_{catch}$) and catch (SDϕ$_{finish}$). Light grey bars reflect the NMC condition, dark gray bars reflect the MC condition. Error bars represent standard errors. For mean-values and standard errors, see Supplementary Materials Table 2.

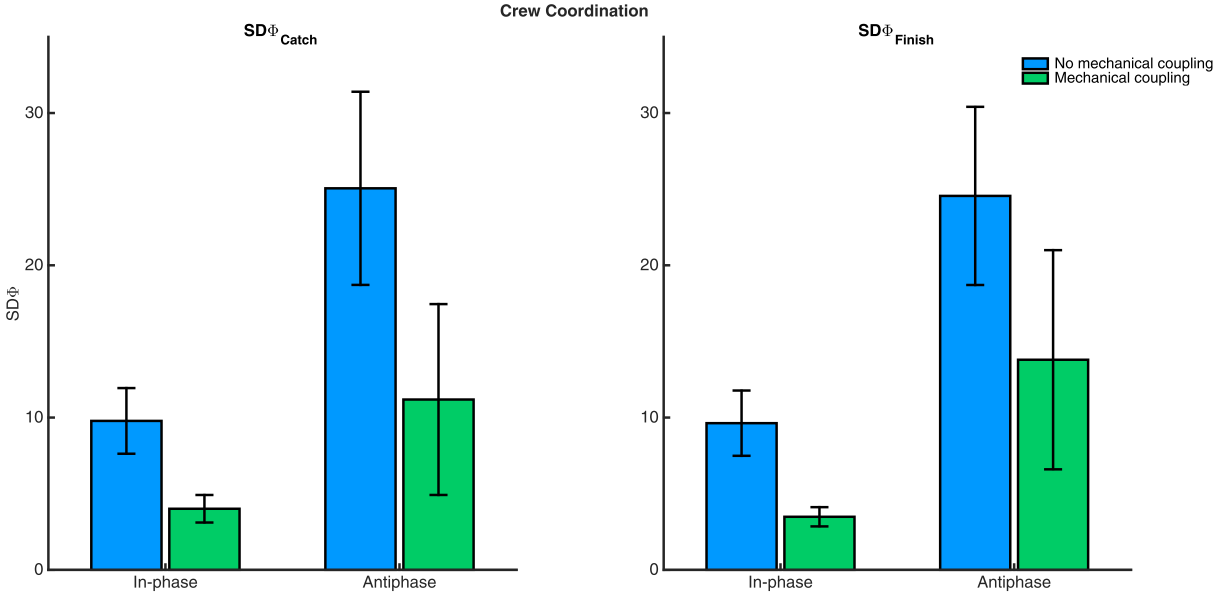

Fig. 4. Variability of relative phase over the complete cycle (SDϕ$_{catch}$) and catch (SDϕ$_{finish}$) averaged over stroke rates. Light grey bars reflect the NMC condition, dark grey bars reflect the MC condition. Error bars represent standard errors.

3.2. Variability of crew coordination

For the nine pairs who did not show any coordinative breakdowns, the variability of coordination[2] was compared over the different conditions and included in the results below. In Fig. 3, the variability of relative phase at the catch ($SD\phi_{catch}$) and finish

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[2] Next to the crew coordination based on the handle movements, we also determined crew coordination based on the CoM positions (similar to Cuijpers et al., 2015 and De Brouwer et al., 2013). This yielded similar results, except for the effect of Tempo for $SD\phi_{catch}$ ($F(1,8) = 5.339, p = .050, \eta p^2 = 0.400$) and the interaction-effect of Coupling x Pattern for $SD\phi_{finish}$ ($F(1,8) = 2.979, p = .123, \eta p^2 = 0.271$). For conciseness, only the results based on the handle (as this is the end-effector of the movement) are presented.

($SD\phi_{finish}$) are displayed (see Table 2 for means and standard errors). The figure clearly shows that for both coordinative measures, crew coordination is less variable for the in-phase pattern and the mechanical coupling conditions. Indeed, both measures of coordinative variability ($SD\phi_{catch}$ and $SD\phi_{finish}$) were significantly affected by Coupling and Pattern, indicating more variable coordination for the NMC condition and the antiphase pattern (see Fig. 3). For $SD\phi_{catch}$ the effect of Coupling was $F(1,8) = 56.67$, $p < .001$, $\eta p^2 = 0.88$ and the effect of Pattern was $F(1,8) = 36.40$, $p < .001$, $\eta p^2 = 0.82$. For $SD\phi_{finish}$ the effect of Coupling was $F(1,8) = 35.57$, $p < .001$, $\eta p^2 = 0.82$ and the effect of Pattern was $F(1,8) = 41.29$, $p < .001$, $\eta p^2 = 0.84$.

Crew coordination variability at the catch ($SD\phi_{catch}$) additionally showed a significant main effect of Tempo ($F(1,8) = 5.48$, $p = .047$, $\eta p^2 = 0.41$), with less variable coordination at the higher than at the lower stroke rate (for $SD\phi_{finish}$ the effect of Tempo was $F(1,8) = 4.590$, $p = .07$, $\eta p^2 = 0.37$).

For both measures ($SD\phi_{catch}$ and $SD\phi_{finish}$) an interaction effect of Coupling × Pattern was present ($SD\phi_{catch}$: $F(1,8) = 14.884$, $p = .005$, $\eta p^2 = 0.65$ and $SD\phi_{finish}$: $F(1,8) = 5.781$, $p = .043$, $\eta p^2 = 0.42$). Post hoc analysis of this interaction effect revealed that differential stability between in- and antiphase is larger in the NMC condition than in the MC condition (see Fig. 4; $SD\phi_{catch}$: all p's < 0.02 and $SD\phi_{finish}$: all p's < 0.01).

4. Discussion

The aim of this study was to investigate the effect of mechanical coupling on the stability of interpersonal coordination for different patterns and at different movement frequencies. The current research question was instigated by the observation that in previous crew rowing experiments (Cuijpers et al., 2015; De Brouwer et al., 2013), no frequency-induced decrease of stability and associated coordinative breakdowns were observed, which is counter to predictions from the HKB-model (Haken et al., 1985). We hypothesized that the mechanical linkage provided such a substantial form of coupling that crew coordination was stabilized so that frequency-induced loss of stability and associated coordinative breakdowns are prevented. To test this hypothesis rowers rowed on ergometers that were connected through slides (mechanical coupling condition) or moved separately (no mechanical coupling condition).

4.1. Coupling strength and differential pattern stability

The mechanical coupling indeed stabilized coordination, as for both coordinative steady state measures crew coordination was less variable in the mechanically coupled conditions. The difference in coordinative stability between in- and antiphase coordination was smaller in the mechanical coupling condition than in the no mechanical coupling condition. Thus, mechanical coupling stabilized *antiphase* coordination to a larger degree than in-phase coordination. This indicates that, although experimentally the coupling manipulation was the same for both patterns, the *effect* of mechanical coupling was most pronounced for antiphase. Possibly, the mechanical coupling had a larger potency to stabilize antiphase than in-phase coordination as antiphase is intrinsically less stable than in-phase (Haken et al., 1985; Kelso et al., 1986; Schmidt & Richardson, 2008). Note that this in line with other empirical findings. In general, experimental manipulations have been shown to have a larger (destabilizing) effect on anti- than in-phase coordination (Kelso, 1995; Schmidt & Richardson, 2008), for instance when implementing a difference in eigenfrequency between the oscillating components (e.g., Amazeen, Schmidt, & Turvey, 1995), increasing movement frequency (e.g., Kelso et al., 1986) or decreasing attention (e.g., Temprado, Zanone, Monno, & Laurent, 2001). As such, stability of antiphase coordination seems more prone to changes in coupling parameters.

Rowing in in-phase coordination was less variable than antiphase coordination and coordinative breakdowns only occurred in antiphase coordination (see also Cuijpers et al., 2015; De Brouwer et al., 2013). This finding is in line with predictions from coupled oscillator models (e.g., Haken et al., 1985). However, there may be an additional explanation, namely that, next to the higher intrinsic stability of the in-phase pattern, the higher variability in the antiphase pattern is related to extensive practice that these experienced rowers have had rowing in in-phase (and not in antiphase). In traditional crew rowing, rowers only row in in-phase coordination. In other words, as for all participants this was the very first time that they rowed in the antiphase pattern, it might be that the higher variability in this pattern can be partly explained by the fact that they tried a new coordinative pattern (see e.g., Freedland & Berthental, 1994; Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1992). Nonetheless, we chose to test experienced rowers to make sure that the variability in their *inter*personal coordination was not obscured by a large variability in their individual movements as can be expected when working with beginners.

The stabilizing effect of the increase in coupling strength through mechanical coupling was not reflected in the occurrence of coordinative breakdowns from anti- to in-phase. Although seven antiphase breakdowns were observed without mechanical coupling and four with mechanical coupling, this difference was not statistically significant. Given that fewer breakdowns occurred in the mechanically coupled condition, this may also be a matter of statistical power. To conclude whether mechanical coupling indeed results in fewer breakdowns, also in other forms and tasks of mechanically coupled interpersonal coordination the effects of mechanical coupling need to be investigated further.

The effect of mechanical coupling is of course dependent on the specific configuration of the physical connection. In the current study, the mechanical coupling through the boat affects the movement in forward and backward direction, which can influence coordinative performance differently than in another direction (for experimental demonstrations with coupled metronomes/clocks, see the review by Kapitaniaka et al., 2012). As such, it is likely that Marmelat and Delignieres (2012) did not find a statistical difference in coordinative stability as a function of mechanical coupling because their participants were coupled in a different plane (frontal) than the sagittal plane in which the pendulums moved. Another interesting endeavor in this regard may be to experimentally manipulate the (passive oscillatory) characteristics of the mechanical coupling source, for instance by adding springs or dampers to the coupling base (see e.g., Ramirez, Aihara, Fey, & Nijmeijer, 2014). This may offer a useful way to systematically manipulate coupling strength. In the case of the ergometer setup, if damping would be maximized, the ergometer system would not be able to move with respect to the ground so that the forces that rowers apply on to the ergometer system are not passed on to the other rowers anymore. In sum, mechanical coupling provides an interesting means to experimentally manipulate coupling in a very controlled way, perhaps more precisely than perceptual forms of coupling, which are for instance more dependent on attention and instructions.

4.2. Movement frequency

The HKB-model predicts that an increase in movement frequency results in a decrease in coordinative stability (Haken et al., 1985; Schmidt & Richardson, 2008). However, some studies have shown that *below* a certain (low) frequency, coordinative stability decreases as well (e.g., Schmidt et al., 1998). This would imply an optimum in movement frequency at which coordination is most stable. We previously suggested that this might also be the case for crew rowing (Cuijpers et al., 2015; 2017). The latter (on-water) study showed that coordinative variability of in-phase on-water rowing for the catch ($SD\phi_{catch}$) decreased over stroke rates 18–26 *spm* and levelled over 26–34 *spm*. In line with this, the current results indeed show that coordinative variability was higher at 20 *spm* than 30 *spm.* In rowing, rowers increase the power per stroke with stroke rate (Hofmijster, Landman, Smith, & Van Soest, 2007). The larger force exchange between the rowers that takes place at 30 *spm* in comparison to 20 spm, may increase the degree to which the rowers influence each other. This influence is not only purely mechanical, but also haptical/kineastetic, as Hill (2002) suggested that the increase in force production provides a better kinaesthetic perception that facilitates the mutual adaption of force patterns. As such, coordinative stability may be higher at 30 than 20 *spm* due to the higher interaction forces.

As stability of crew coordination was lower (given the observed higher steady state coordinative variability) at 20 *spm* than at 30 *spm*, based on empirical grounds one could expect more coordinative breakdowns at the *lower* stroke rate. In line with predictions of the HKB-model, our results revealed coordinative breakdowns in (only) antiphase coordination, yet the occurrence of these breakdowns was not affected by movement frequency; six antiphase breakdowns were observed at 20 *spm* and five at 30 *spm*. This questions whether the observed coordinative breakdowns were a consequence of a loss of coordinative stability. More likely, they may have been following a perturbation such as a temporary loss of attention (see also Cuijpers et al., 2015), as the pairs were often able to restore coordination within the next cycle and then continued to row in the intended pattern.

5. Conclusion

In this study, we investigated the effect of mechanical coupling on the stability of interpersonal coordination for different patterns and at different movement frequencies in a crew rowing task. In summary, the mechanical coupling stabilized coordination, even more so for the intrinsically less stable anti- compared to in-phase pattern. This suggests that antiphase coordination may be more prone to changes in coupling parameters than in-phase coordination. Counter to predictions from coupled oscillator models, but in line with previous studies on crew rowing, coordinative variability was higher at the lower stroke rate. This may be related to higher interaction forces at 30 *spm* than at 20 *spm*. Next, although coordinative breakdowns only occurred in antiphase rowing (as can be expected based on coupled oscillator models), the occurrence of coordinative breakdowns did not follow the lower coordinative variability when mechanically coupled, nor at the higher stroke rate: no effect of coupling nor tempo was found. This suggests that these coordinative breakdowns are not necessarily due to a decrease in coordinative stability, but may rather be caused by a perturbation, such as a temporary loss of attention.

Together, the results provide a first insight in the stabilizing effects of mechanical coupling on interpersonal coordination. We showed that mechanical coupling provides an interesting means to experimentally manipulate coupling, for instance through implementing different configurations of the coupling source. As many interpersonal tasks involve mechanical coupling and, given that mechanical coupling can be manipulated in a specific and systematic way, this seems a direction worth investigating further.

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Appendix A. Supplementary data

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