Coordination dynamics in crew rowing

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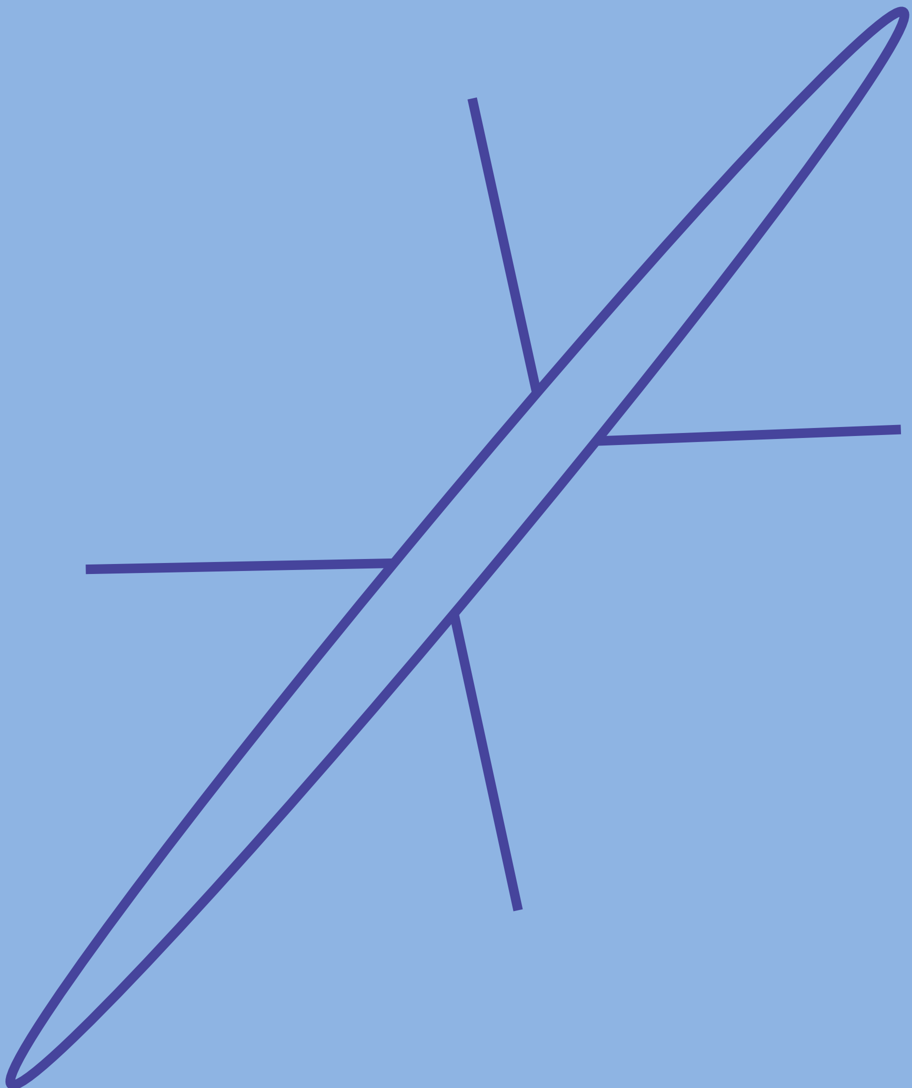
Exploring the potential benefits of antiphase crew rowing on water

Chapter 7



Laura S. Cuijpers, Frank T.J.M. Zaal, Alexander Hoogerheide, Koen A.P.M. Lemmink, & Harjo J. de Poel *(submitted)*. Exploring the potential benefits of antiphase crew rowing on water.

Abstract

Rowing crews synchronise strokes to achieve optimal performance. Curiously, antiphase synchrony (i.e., *alternating* strokes) may reduce velocity fluctuations of the boat, which would theoretically imply reduced hydrodynamic drag and, hence, potentially faster race times. We experimentally compared in-phase to antiphase rowing in terms of crew coordination and effects on boat kinematics and race time. Nine pairs of experienced rowers rowed four 1000 *m* trials in in-phase and antiphase at 20 and 30 strokes per minute. Despite that it was their first attempt, most crews performed the unconventional antiphase pattern stably. Antiphase rowing indeed reduced boat velocity fluctuations, especially at higher pace, but did not yield higher speed. Nevertheless, antiphase rowing may be further improved through practice and optimisation of boat design. Together, these results provide quite promising future implications regarding antiphase rowing. More generally, this illustrates how complementarity, rather than mere synchrony, may be more beneficial for group performance.

Introduction

In crew rowing, rowers need to coordinate their movements as one team to optimise performance. It is therefore that crew rowing is often quoted as the prime, natural example of group dynamics, interpersonal coordination and joint action (e.g., De Poel, De Brouwer, & Cuijpers, 2016). Although traditionally the rowers of a crew strive to row in perfect in-phase synchronisation, it has been suggested that rowing in antiphase (i.e., alternating strokes) may reduce hydrodynamic drag and potentially yield faster racing times (e.g., Brearly, DeMestre, & Watson, 1998; Cuijpers, Zaal, & De Poel, 2015; De Brouwer, De Poel, & Hofmijster, 2013; Greidanus, Delfos, & Westerweel, 2016). Though controversial and subject to debate (e.g., Western Mail, 1929; The Argus, 1929; Northern Star, 1929; Nolte, 2007), empirical backup testing antiphase crew rowing on-water rowing is however lacking. After a series of lab studies (Cuijpers et al., 2015; Cuijpers, Den Hartigh, Zaal, & De Poel, 2019; de Brouwer et al., 2013), we now set out to test the potential benefits of antiphase rowing in an experiment on the water.

The rowing cycle

The rowing cycle consists of two phases. The drive phase starts with the rowers placing their blades in the water (which is called the catch), after which the rowers propel the boat forward through the water by putting pressure on their blades. At the end of the drive, the rowers release their blades out of the water (the so-called 'finish') and return to their initial catching position during the recovery phase. As a result, the boat is only propelled forward during part of the rowing cycle. In addition, the rowers move their relatively heavy center of mass back and forth across the length of the relatively light boat, which decelerates the boat as they push off against the boat, and accelerates the boat when they return to the catch (Hill & Fahrig, 2009). Thus, the discontinuous propulsion together with the movements of the rowers with respect to the boat make that the velocity of the boat fluctuates within each rowing cycle (Hill & Fahrig, 2009).

As the power to overcome the resistance of the water is related to the velocity of the boat to the third power (i.e., in order to row twice as fast, the rowers need to produce eight times more power; e.g., Hofmijster, Landman, Smidt, & Van Soest, 2007), it would be most efficient to maintain a constant boat velocity throughout the rowing cycle (Brearly et al., 1998; Cuijpers et al., 2015; De Brouwer et al., 2013; Greidanus et al., 2016; Hofmijster 2007; Hill 2009). As shown by the sliding rigger invention[10], decreased velocity fluctuations of the boat indeed had a large effect on race times, as was successfully proved during the skiff events (i.e., single rower) of the 1981-1983 Rowing World Championships, after which the sliding rigger was banned from competition in 1983 due to its high costs that would be an unfair disadvantage for the less privileged (Angst, 1982).

Interestingly, crews may be able to minimise surge velocity fluctuations without such technological advancements. Both in science and in practice, the general idea is that if crew members perfectly synchronise their movements, detrimental movements of the boat such as surge velocity fluctuations can be minimised (O'Brien, 2011; Wing & Woodburn, 1995). This would then result in an optimised conversion of the power that rowers produce into forward speed (e.g., Baudouin & Hawkins, 2002; Brearly et al., 1998; Hill & Fahrig, 2009; Martin & Bernfield, 1980). However, recent research demonstrated that enhanced crew coordination actually came with *larger* surge velocity fluctuations (Cuijpers, Passos, Hoogerheide, Murgia, Lemmink, & De Poel, 2017). This may, perhaps somewhat counterintuitively, suggest that *deviations* from perfect synchrony may actually reduce velocity fluctuations of the boat and, hence, hydrodynamic drag.

Potential benefits of antiphase rowing

In theory, by rowing in an antiphase pattern a crew may be able to minimise velocity fluctuations of the boat and thereby reduce the associated power losses with 5-6% (Brearley et al., 1998; Hill & Fahrig, 2009; Hofmijster et al., 2007). The boat is propelled more continuously through the water, as the rowers alternate their propulsive phases with each other. If the crew members would be able to perfectly align their drive with the recovery of their crew member and vice versa, propulsive force would actually be applied continuously on the water. Furthermore, they would also move their bodies towards and away from each other, nulling their combined centre of mass displacement. It has been estimated that the reduction in power losses may lead to a gain of a boat length for an eight on a 2000 *m* race (Brearly et al., 1998), which would be a substantial advantage given that races at World Cup level are often decided by differences within hundreds of a second (O'Brien, 2011).

Interestingly, there are several records of trying such alternative (i.e., other than in-phase) crew rowing patterns on-water. For instance, in 1929 the English tried rowing alternating four subgroups of two rowers, inspired by the

[10] The sliding rigger invention involved that the light rigger (incl. footboard) moves across the length of the boat while keeping the seat (and thus the relatively heavy *CoM* of the rower) fixated on the boat (Angst, 1982).

quarter-cycle difference of four-pistol engines[11]. Although there are newspaper articles that report that the attempts in England were successful (see e.g., Dodd, 2006; The Daily News, 1929) there is no formal data reported to support that. Notably, a recent study that tested miniature robots rowing at a 45° pattern in a pool[12] showed that velocity fluctuations indeed decreased, but mean boat velocity as well, so that the 45° pattern did not go faster than the in-phase pattern (Boucher, Labbé, Clanet, 2017). One of the reasons why rowing 45, 60, or 90° out of phase (e.g., Cairns Post, 1932; MacMillan, 2000) may not yield positive results may be that such phase relations are intrinsically unstable (Haken, Kelso, & Bunz, 1985). Indeed, empirical studies showed that coordination patterns other than in- and antiphase are not stable without training, let alone between persons (Wilson, Collins, & Bingham, 2005; Kostrubiec, Zanone, Fuchs, & Kelso, 2012; Schöner & Kelso, 1988; Zanone & Kelso, 1992). We tested this in a pilot study, in which rowers tried to row with a quarter cycle difference (i.e., 90°) at separate ergometers, and observed that coordination already broke down at 24 *spm*, while antiphase rowing was easily maintained (De Poel et al., 2016). Therefore, in our subsequent experiments, we considered antiphase crew rowing, i.e. rowing in the intrinsically stable 180° pattern (De Poel et al., 2016; Haken, et al., 1985; Schmidt & Richardson, 2008). Although the Russians supposedly tried rowing in antiphase in the late 1970's, and German try-outs have been reported (Von Opel, 1963; Munk, 2002), the potential benefits of antiphase rowing have not been experimentally tested, let alone verified on the water.

Recent lab studies (De Brouwer et al., 2013; Cuijpers et al., 2015; 2019), in which pairs of rowers rowed in in- and antiphase patterns on coupled ergometers on slides (allowing them to move with respect to the ground), demonstrated that the movements of the ergometer system (mimicking the velocity fluctuations of the boat on water) were much smaller when rowing in antiphase as compared to in-phase coordination. Moreover, rowers were able to produce similar power in antiphase as in in-phase coordination (De Brouwer et al., 2013). The latter is important, because even if rowing in antiphase would reduce power losses, it would not be effective if it also limited power production (Cuijpers et al., 2017; Hofmijster et al., 2007). Together, the lab results suggest that rowing in antiphase coordination might indeed have the potential to improve race times compared to rowing in in-phase coordination.

Although the above-described results provide a positive indication for antiphase rowing, the results obtained from the more controlled laboratory

[11] Footage of the so-called "Jazz-rowing" is available at: https://www.youtube.com/watch?v=zQ6fxsmo3V8.

[12] Footage of that experiment can be found here: https://physicstoday.scitation.org/doi/10.1063/PT.3.3606

situation cannot be directly generalised to the water without reservations, because on water various other aspects come into play. For instance, in the lab setup the rowers and the ergometer system remained at more or less the same position in space (see, e.g., the videos in the supplementary material of Cuijpers et al., 2015; 2019), while on the water, evidently, the boat has actual forward speed. Moreover, in a boat on the water, rowers also have to maintain their lateral balance, while an ergometer system cannot move in lateral direction. Furthermore, on water the rowers need to account for environmental factors such as water and wind that may perturb coordination, e.g., when a blade hits a wave. Also, on the ergometers, the rowers pull a lightweight handle that is attached to an individual flywheel, while on the water, the pressure on the blades depends on the velocity of the boat, as the oars are connected to the boat via the riggers. As the movements of the boat depend on the forces that the rowers apply onto the blades, this means that the rowers would need to apply a constant force over their drive phases and perfectly alternate their drive- and recovery phase to cancel out velocity fluctuations. Hence, if on water the antiphase rowing indeed results in less velocity fluctuations of the boat, the distribution of force that the rowers apply over the drive may change as well. Such issues may have implications for the coordination of the individual rowing movement and thus also for the coordination of the crew. Therefore, in the current experiment we test rowing crew coordination in both in- and antiphase on the water.

Crew coordination

While from a biomechanical perspective rowing in antiphase may be more efficient, it has been argued from a coordination dynamics perspective that rowing in antiphase may be more challenging than in in-phase coordination (De Poel et al., 2016; Nolte, 2007). This argument arrives from the many studies of cyclic interpersonal coordination tasks, such as moving handheld pendulums or rocking chairs in a coordinated fashion, which demonstrated that the stability of antiphase coordination is lower than that of in-phase coordination (e.g., Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt & Richardson, 2008). Next to that, these studies demonstrated that when movement frequency increases, the stability of coordination decreases, even more so for antiphase coordination. At a critical frequency, antiphase coordination became unstable and a transition to the remaining stable in-phase coordination pattern took place (e.g., Schmidt, Carello, & Turvey, 1990). As in crew rowing stroke rates can reach up to 46 strokes per minute (*spm*) in on-water racing, antiphase coordination needs to remain sufficiently stable at high movement rates in order to be successful in competition. In fact, in the laboratory rowing pairs proved able to maintain rowing in antiphase fashion for stroke rates up to 36 *spm* (de Brouwer et al., 2013; Cuijpers et al., 2015) and some pairs even up to 42 *spm* (Cuijpers et al., 2015). Nonetheless, in line with theoretically motivated expectations (Haken, Kelso, & Bunz, 1985) and previous studies on interpersonal coordination (Schmidt & Richardson, 2008), coordinative breakdowns (i.e., rowers falling out of their instructed pattern) only occurred when rowing in an antiphase pattern (De Brouwer et al., 2013; Cuijpers et al., 2015; 2019). In a similar vein, antiphase crew coordination was found to be significantly more variable than in-phase coordination (Cuijpers et al., 2019; De Brouwer et al., 2013). Interestingly, for both in- and antiphase, crew coordination was poorer at 20 than at 30 *spm* (Cuijpers et al., 2019), which does not correspond to findings in other coordination dynamics studies (e.g., Schmidt et al., 1990). Also, the occurrence of antiphase breakdowns did not seem to be related to movement tempo (De Brouwer et al., 2013; Cuijpers et al., 2015; 2019). More so, the reduction of ergometer movements compared to in-phase rowing was even more pronounced for higher stroke rates (Cuijpers et al., 2015). Together, this already suggests that at higher (racing) stroke rates rowing in antiphase may even be less difficult to maintain and more drag-reducing than at lower rates. In sum, while predictions from coordination dynamics suggest that rowing in antiphase may be challenging, especially at high movement rates, lab results suggest that antiphase crew coordination is not as difficult as it might intuitively seem and that it may actually be easier and more beneficial when performed at higher (racing) rates.

Aim

The results from previous lab studies provide a positive indication for antiphase crew coordination: on coupled ergometers, rowers are able to row in antiphase coordination, also at the higher (racing) stroke rates (Cuijpers et al., 2015; 2019). In addition, the displacement of the coupled ergometer system, reflecting velocity fluctuations in de laboratory set up, was less when the rowers rowed in antiphase compared to in-phase coordination (Cuijpers et al., 2015; De Brouwer et al., 2013). The next step is to take the antiphase rowing from the lab to the water. Are rowers also able to row in antiphase in (changing conditions of) water and wind, when they have to propel a boat forward through the water, while many other things (e.g., pressure on the blades) also alter compared to the normal in-phase rowing? Here we take an initial step that aims to verify whether the kinematic differences observed in the lab between in- and antiphase rowing also hold on the water. Does rowing in antiphase indeed minimise surge velocity fluctuations in a boat that is moving through the water and does this result in faster racing times?

Method

Participants

Eighteen rowers, paired in nine crews, participated in the experiment (8 women, 10 men; age 23 ± 5 years; body height 1.83 ± 0.09 *m*; body mass 75 ± 11 *kg*; rowing experience 6 ± 4 years). 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. Methodologically speaking, it would be cleanest to compare in- and antiphase rowing in crews that have the same amount of experience in in- as in antiphase. However, rowing on the water, especially in a double scull (a two-person boat in which each rower is handling two oars), requires skill that can only be acquired through prolonged practice, which currently is only done in in-phase crew coordination. Therefore, in the current experiments only rowers who rowed competitively for at least one year on national level (implying at least one year of practicing rowing 7-8 times a week) and who had experience in sculling (handling two oars) could partake in our experiment. As rower's generally only row in in-phase coordination, this means that the rowers in our experiment had extensive practice rowing in in-phase, but never rowed in antiphase before. For more detailed information on the different pairs, see Table 1 in Supplementary Materials.

Experimental setup

Trials were performed in a quad (i.e., four-persons rowing boat, in which each rower is handling two oars; see Supplementary Materials Table 2 for rigging and specifications of boat and oars), leaving the two middle seats empty to allow for sufficient space for the oars not to collide. The horizontal angles of the oars, reflecting the stroke movements of both rowers, were measured using potentiometers (Bourns, 6639 Precision Potentiometer, 200 *Hz*). Movements of the boat in terms of linear accelerations and angular velocities were sampled with a three-axial accelerometer-gyroscope sensor (MPU-6050, InvenSense Inc., 200 *Hz*), and longitude and latitude of the boat was registered using a GPS sensor (PmodGPS, Digilent Inc., sampling rate: 1 *Hz*). These sensors were placed in a waterproof housing secured to the boat behind the bow rower (i.e., in direction to the bow of the boat). The outputs of these different sensors were sampled on a microcontroller (MyRio-1900, National Instruments) and written onto a SD-card within the waterproof housing. The 1000 *m* trials were timed using a stopwatch (Fasttime 14). Heartrate of both rowers was measured using a heartrate monitor (Polar M400, 1 *Hz*).

Protocol

To warm up, each crew started rowing towards the start of the race course (about 15-20 *min* warming up at 18-22 *spm*). Half of this warming up was used to practice antiphase rowing. The crews performed four 1000 m trials, two in in-phase and two in antiphase. Each pattern was performed both at 20 *spm* (as is common in endurance training) and at 30 *spm* (comparable to racing rates). To minimise influences of current and wind, trials were always performed on the same part of the course and in the same direction. This meant that the crews rowed back for 1000 *m* to the start of the course after each trial, during which they prepared for the next trial by rowing in the same pattern as the following trial would be. At the start and at the end of the trial there was a break of 30 *s* in which rowers had to keep their oars perpendicular to the boat, with the blades resting on the water. This was done to (re-)determine initial values of the accelerometer and gyroscope sensor and the oar angles. The 1000 m trials were performed with a running start, so that the boat was up to speed when crossing the starting line. Rowers were instructed to maintain a comparable intensity in both the in- and antiphase patterns and received feedback about their heartrate on a heartrate monitor. The stroke rower (i.e., the rower crossing the finish last) received real-time feedback about stroke rate on an on-board computer with a small display (Speed Coach GPS-II, Nielsen Kellerman, US).

Data analysis

Kinematic time series were analysed using customised procedures in Matlab (MathWorks, USA). The time series were corrected for initial position of the sensors using the average sensor values as obtained in the first 30 *s* rest bin (see above). The time series were interpolated using a piecewise spline and were low-pass filtered using a bi-directional second order Butterworth filter with a cut-off frequency of 4 *Hz* for the oar angle time series, 20 *Hz* for the accelerometer time series and 15 *Hz* for the gyroscope time series (e.g., Cuijpers et al., 2017; Sabatini, Martelloni, Scapellato, & Cavallo, 2005). After this, the sensor values in *mV* were converted into oar angles (°), linear accelerations (m/s^2) and angular velocities (°/*s*). For further analysis, for all crews, steady state bins of 60 cycles were determined for each 1000 *m* trial (see below).

Crew coordination

The spatio-temporal relation between starboard and port of each individual rower (reflecting intrapersonal coordination) and between the rowers' oar angles for both starboard and port (reflecting interpersonal coordination) around catch and finish was expressed by the discrete relative phase[13]. The discrete measure of relative phase based on point-estimates of oar angle extrema near the catch and finish of the stroke was calculated for each full cycle as:

$$\phi_{PEi}(t) = \frac{t_{2,j}-t_{1,j}}{t_{2,j+1}-t_{2,j}}360° \quad \text{(Eq. 7.1)}$$

in which $t_{1,j}$ and $t_{2,j}$ indicate the time of the j^{th} peak of the oar angle of starboard and port or rower 1 and 2. The instances of catch and finish were determined as the minimum (catch) and maximum (finish) excursions of the signal using a custom made peak-picking algorithm.

Dependent measures

For all trials, deviations from steady state (coordinative breakdowns), defined as a deviation of relative phase value ≥ 180° of the instructed pattern for at least one complete movement cycle, were counted (see Cuijpers et al., 2019). Next, for the steady state trials (in which no coordinative breakdown occurred), the time series were analysed over steady state bins (60 *cycles*) for each condition. For each trial, mean absolute error (*AE*) with respect to the instructed pattern (0° for in- and 180° for the antiphase pattern) and standard deviations (*SD*) of discrete relative phase ($AE\phi_{catch}$ and $SD\phi_{catch}$ and $AE\phi_{finish}$ and $SD\phi_{finish}$, for catch and finish, respectively) were calculated as measures of coordinative performance. As the drive and recover differ in duration (Cuijpers et al., 2017; Hill, 2002), especially at lower stroke rates, which is likely to influence movements of the boat, the drive-recover ratio (*ratio*) is reported. Movements of the boat[14] are reported in terms of fluctuations (expressed in standard deviations) of surge and heave (based on the accelerometer timeseries) and pitch and roll (based on the gyroscope timeseries), as represented by *SDsurge, SDheave, SDpitch* and *SDroll* (see also Cuijpers et al., 2017). Finally, race times and average heartrate (to control for

[13] As the rowing cycle deviates from perfect harmonicity, especially at lower stroke rates, we determined accuracy and variability of crew coordination based on the discrete measure of relative phase that is not sensitive to within-cycle harmonicities (Cuijpers et al., 2015; 2019).

[14] As rowers both rowers handle two oars in sculling, they can correct for yawing individually (i.e., they do not need to coordinate their movements *together* to make the boat run straight). Next, boat movements in terms of sway are unlikely to occur (if any, due to wind or current, rather than affected by crew coordination). Therefore, we choose to report surge, heave, roll and pitch, as these are boat movements that can be influenced by crew coordination.

differences in effort between in- and antiphase) for each rower are reported for each condition.

Statistical analysis

Each of the above-mentioned steady state dependent measures was subjected to a 2 Pattern (in- and antiphase coordination) x 2 Tempo (20 and 30 *spm*) repeated measures ANOVA. An α of 0.05 was adopted for all tests of significance. If necessary, interaction effects were further scrutinised via Bonferroni-corrected post-hoc paired-samples *t*-tests.

Results

Coordination breakdowns

Although performing an antiphase pattern for the first time, all nine pairs were able to row at least one antiphase trial without coordinative breakdowns. Five pairs were able to row in all trials without a single coordinative breakdown, while two other pairs only showed a coordinative breakdown once (one pair while rowing at 20 *spm* and the other pair while rowing at 30 *spm*). Breakdowns in crew coordination only occurred in antiphase. Finally, in two pairs, antiphase coordination repetitively broke down, three and four times in one 1000 *m* trial, respectively, while rowing at 30 *spm*. The subsequent results on boat movements, race time and crew coordination are based on the five pairs[15] that did not show any coordinative breakdowns. An example of the obtained kinematic time series for the different experimental conditions is shown in Figure 1.

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[15] As including only 5 pairs in the RM Anova limits statistical power, we also tested the effects of Pattern based on 8 pairs that managed to row in in- and antiphase at 20 *spm* without showing coordinative breakdowns, which showed statistical results. The effects of Pattern based on 8 pairs at 20 *spm* were: $SD\phi_{catch}$ ($F(1,7) = 31.05$, $p < .01$, $\eta p^2 = .82$), $SD\phi_{finish}$ ($F(1,7) = 29.56$, $p < .01$, $\eta p^2 = .81$), $AE\phi_{finish}$ ($F(1,7) = 7.85$, $p < .05$, $\eta p^2 = .56$), *ratio* ($F(1,7) = 2.35$, $p = .17$, $\eta p^2 = .25$), *SDsurge* ($F(1,7) = 68.350$, $p < .001$, $\eta p^2 = .91$), *SDheave* ($F(1,7) = 0.06$, $p = .81$, $\eta p^2 = .01$), *SDpitch* ($F(1,7) = 0.61$, $p = .46$, $\eta p^2 = .08$) and *SDroll* ($F(1,7) = 1.69$, $p = .24$, $\eta p^2 = .20$). As in the latter analysis only the results at 20 *spm* are included, the effects of Tempo could not be tested.

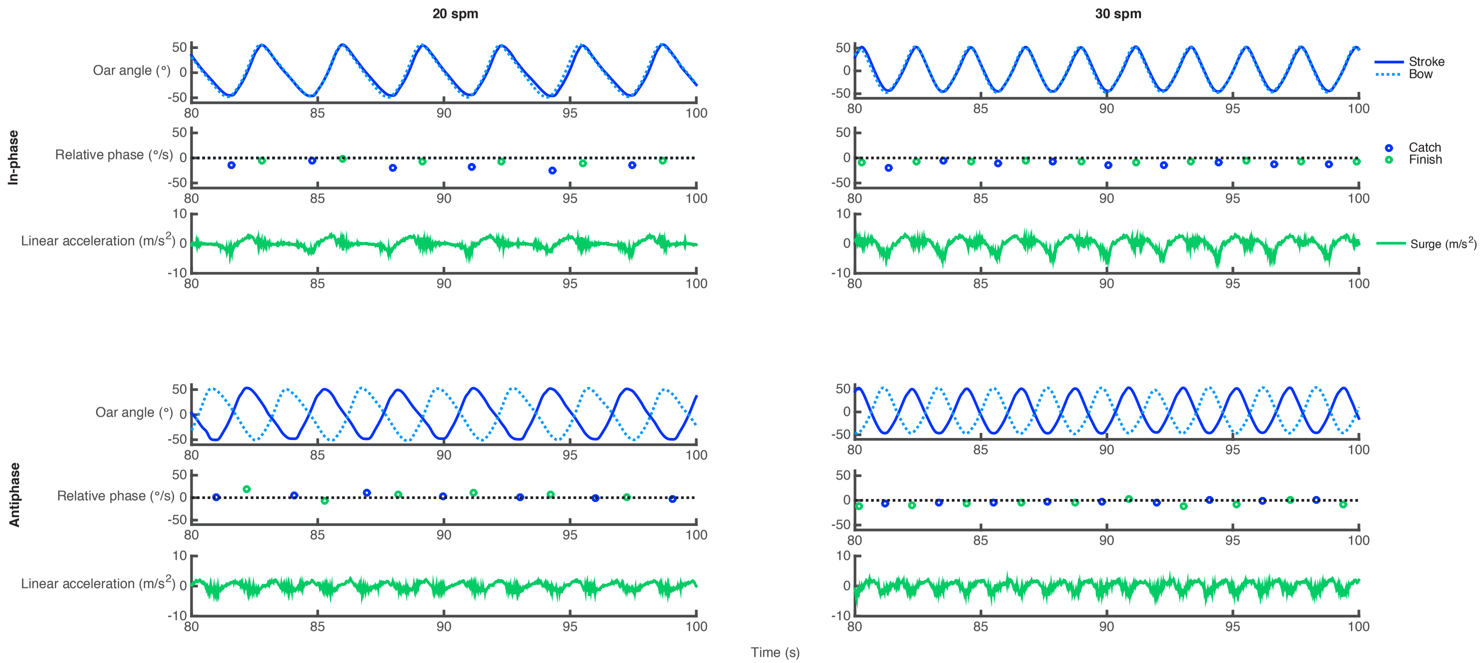

Figure 1. Example of kinematic time series for the different experimental conditions: in-phase and antiphase at 20 and 30 spm. Each panel depicts the oar angles of both rowers, the discrete relative phase with respect to the intended pattern around catch and finish and movements of the boat in terms of surge velocity fluctuations.

Boat movements

Velocity fluctuations in terms of *SDsurge* are shown in Fig. 2A. *SDsurge* was significantly affected by Pattern, confirming that rowing in antiphase reduced within-cycle velocity fluctuations compared to in-phase crew rowing ($F(1,4) = 25.98$, $p = .001$, $\eta p^2 = .96$). *SDsurge* significantly increased with Tempo ($F(1,4) = 103.97$, $p = .001$, $\eta p^2 = .96$). The reduction in surge velocity fluctuations when rowing in antiphase was even more pronounced at the higher stroke rate, as indicated by an interaction effect of Pattern × Tempo ($F(1,4) = 112.87$, $p < .001$, $\eta p^2 = .97$). Post-hoc tests showed significant differences between antiphase coordination at 20 and 30 *spm* ($p < .05$), in-phase coordination at 20 and 30 *spm* ($p < 0.001$), in- and antiphase coordination at 20 *spm* ($p < .05$) and in- and antiphase coordination at 30 *spm* ($p < .001$). As can be seen in Fig. 1, the example of the obtained kinematic time series clearly showed less surge velocity fluctuations when rowing in antiphase compared to in-phase coordination, especially at 30 *spm.* As here we focus on the effects of crew coordination on surge velocity fluctuations, the effects on heave, pitch and roll[16] are given in footnote 3 (for mean values and standard errors, see Supplementary Materials Table 3.

Race time

All pairs were able to perform the two instructed stroke rates and rowed at similar heart rates for in- and antiphase (as instructed), indicating that rowers produced a similar amount of effort in both the in- and antiphase conditions (see Supplementary Materials Table 3. for mean values and standard errors). Figure 1B shows faster racing times while rowing in in-phase with respect to antiphase coordination, which is supported by an effect of Pattern ($F(1,4) = 16.38$, $p < .05$, $\eta p^2 = .80$). Unsurprisingly, racing times were faster at 30 compared to 20 *spm* as supported by an effect of Tempo ($F(1,4) = 77.46$, $p = .001$, $\eta p^2 = .95$).

[16] *SDheave* and *SDpitch* were higher at 30 than at 20 *spm*. The significant of Tempo was $F(1,4) = 68.64$, $p = .001$, $\eta p^2 = .95$ for *SDheave* and $F(1,4) = 10.03$, $p < .05$, $\eta p^2 = .72$ for *SDpitch*. *SDheave* and *SDpitch* were not significantly affected by Pattern. *SDroll* was not significantly affected by Pattern nor Tempo.

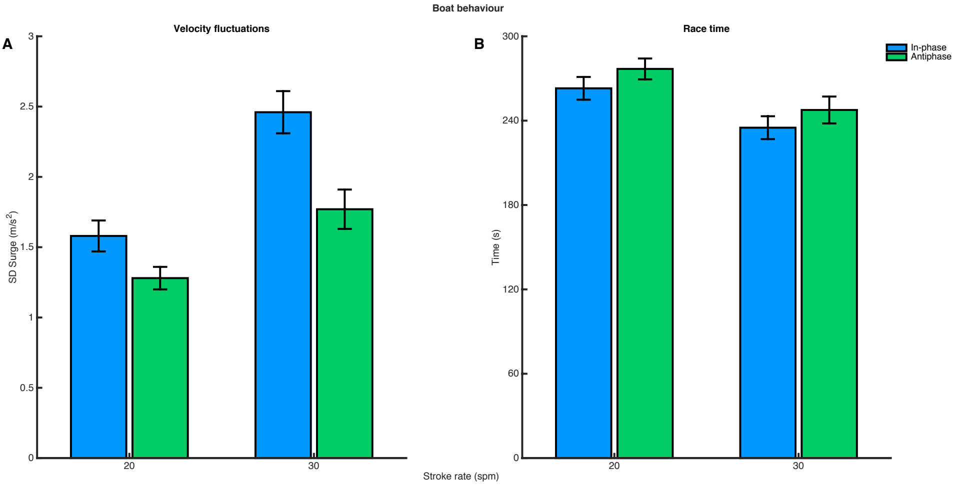

Figure 2. Velocity fluctuations (A) and race times (B) for in- and antiphase at 20 and 30 spm. Error bars represent standard errors.

Crew coordination

The variability of coordination[17] was compared over the different conditions and included in the results below. Fig. 2 shows an example of the obtained time series, showing the oar angles of the rowers coinciding (hence overlapping) in in-phase and alternating in antiphase coordination. In Fig. 3 the variability of relative phase at the catch ($SD\phi_{catch}$; panel A) and finish ($SD\phi_{finish}$; panel B) are displayed (see Table 3 for means and standard errors). The figure clearly shows that for both coordinative measures, crew coordination was less variable for the in-phase pattern and the higher stroke rate. Indeed, $SD\phi_{catch}$ and $SD\phi_{finish}$ were significantly affected by both Pattern and Tempo, indicating more variable coordination for the antiphase pattern and the lower stroke rate (see Fig. 2A and B). For $SD\phi_{catch}$ the effect of Pattern was $F(1,4) = 21.06$, $p = .01$, $\eta p^2 = .84$ and the effect of Tempo was $F(1,4) = 14.12$, $p < .05$, $\eta p^2 = .78$. For $SD\phi_{finish}$ the effect of Pattern was $F(1,4) = 21.82$, $p = .01$, $\eta p^2 = .85$ and the effect of Tempo was $F(1,4) = 13.34$, $p < .05$, $\eta p^2 = .77$. Crew coordination variability at the finish ($SD\phi_{finish}$) additionally showed a significant interaction effect of Pattern × Tempo ($F(1,4) = 8.36$, $p < .05$, $\eta p^2 = .68$) indicating a significant decrease in coordinative variability from 20 to 30 *spm* for the antiphase pattern ($p < .05$). Post hoc tests showed significant differences between antiphase coordination at 20 and 30 *spm*

[17] Variability and accuracy of crew coordination was calculated for both starboard and port, yielding similar results, except for $AE\phi_{finish}$ (the effect of Pattern was only present for port and not for starboard). For conciseness, only the results based on port are presented.

(p < .05), in- and antiphase coordination at 20 *spm* (p < .05) and in- and antiphase coordination at 30 *spm* (p < .05), but not for in-phase coordination at 20 and 30 *spm* (p = 0.108). For $SD\phi_{catch}$, the interaction effect of Pattern × Tempo was just above the significance threshold ($F(1,4) = 7.29$, $p = .054$, $\eta p^2 = .65$).

The accuracy of crew coordination was calculated as the absolute error with respect to the intended pattern (e.g., the deviation from 0° in Fig. 1). Fig. 4A and B suggest that antiphase coordination was performed less accurately than in-phase coordination (see Table 3. for means and standard errors), though only for $AE\phi_{finish}$ (fig. 4B) on the port side a significant effect of Pattern was present ($F(1,4) = 11.05$, $p < .05$, $\eta p^2 = .73$).

The drive-recovery ratio (Fig. 5) increased with stroke rate ($F(1,4) = 54.30$, $p < .01$, $\eta p^2 = .93$), indicating that drive and recovery became more equal in duration at 30 *spm* (reflected in a value closer to 1; see Supplementary Materials Table 3. for means and standards errors; see also the moments of catch and finish in Fig. 1 that are more evenly distributed at 30 *spm*an than at 20 *spm*). Further, an interaction effect of Pattern × Tempo ($F(1,4) = 11.41$, $p < .05$, $\eta p^2 = .74$) indicated that in-phase drive-recovery ratio was significantly lower than antiphase at 20 *spm*. Post hoc tests showed significant differences between antiphase coordination at 20 and 30 *spm* (p < .01), in-phase coordination at 20 and 30 *spm* (p < .01) and in- and antiphase coordination at 20 *spm* (p < .05), but not for in- and antiphase coordination at 30 *spm* (p = 0.314).

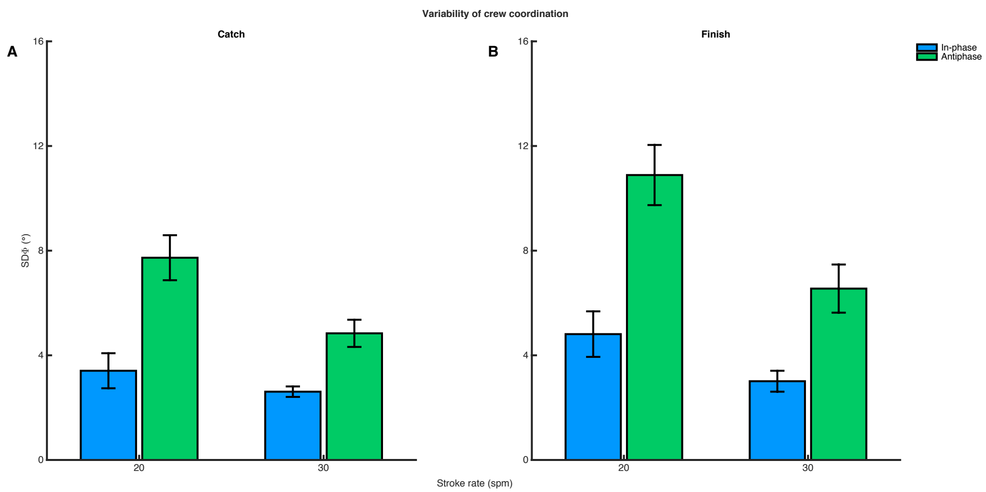

Figure 3. Variability of crew coordination around the catch (A) and finish (B) for in- and antiphase at 20 and 30 spm. Error bars represent standard errors.

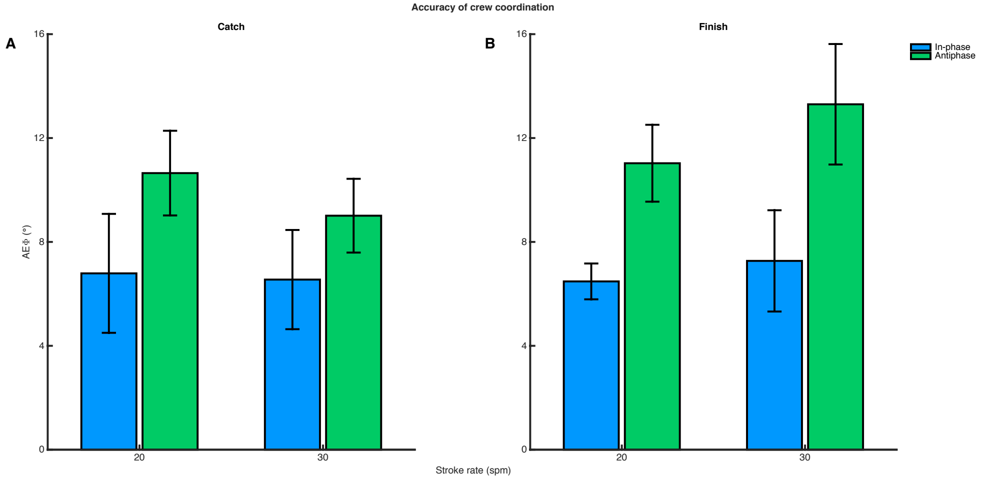

Figure 4. Accuracy of crew coordination around the catch (A) and finish (B) for in- and antiphase at 20 and 30 spm. Error bars represent standard errors.

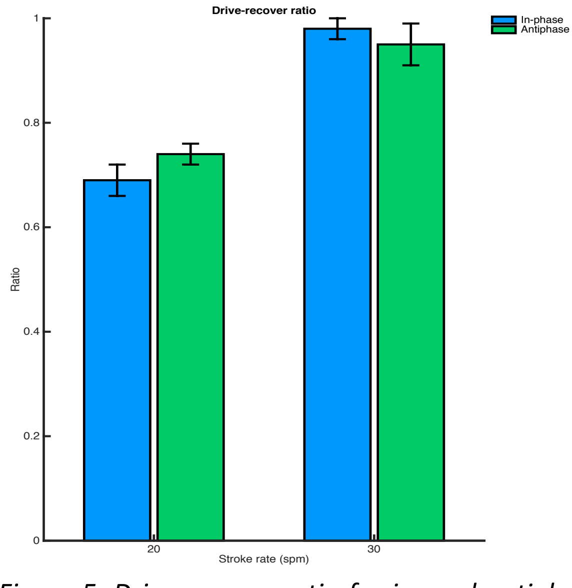

Figure 5. Drive-recover ratio for in- and antiphase at 20 and 30 spm. Error bars represent standard errors.

Discussion

The aim of this study was to test whether rowers were able to row in an antiphase pattern on the water. Next, we aimed to verify whether antiphase rowing on water indeed minimised surge velocity fluctuations and whether this would yield a higher boat speed. We tested nine pairs rowing four 1000 *m* trials in a four-person rowing boat that was modified for two rowers, while they rowed in in-phase and antiphase crew coordination at 20 and 30 *spm*.

Crew coordination

The rowers in the present study had never rowed in antiphase before. Still, already at these first attempts they managed quite well to row in this pattern. Coordinative breakdowns only occurred occasionally and only in antiphase. In other words, we repeated the promising results obtained in previous experiments in the lab (De Brouwer et al., 2013; Cuijpers et al., 2015; 2019), now on water. Seven out of the nine pairs were able to perform all trials, with only two incidental breakdowns from the antiphase rowing pattern. During these two incidental breakdowns, the pairs were able to immediately restore crew coordination within the next rowing cycle, and continued rowing in antiphase for the rest of their trial. In two other pairs, antiphase coordination broke down repetitively within their 30 *spm* trial, while at 20 *spm* no breakdowns occurred. Crew coordination was less variable for the in-phase compared to the antiphase pattern. Especially antiphase coordinative variability was lower at 30 compared to 20 *spm*, which suggest that antiphase rowing may be performed more consistently at higher racing stroke rates than at lower (endurance) training stroke rates. The fact that the two pairs that broke down in coordination repetitively seemed to have more trouble rowing at 30 *spm* than at 20 *spm* does not fit well with the variability observed in pairs that did not show coordinative breakdowns. As for these two pairs the breakdowns occurred at the stroke rate at which antiphase performance was least variable, and given that two other pairs were able to restore crew coordination within the next cycle, this supports the idea that antiphase breakdowns were not related to a frequency-related loss of stability, but likely occurred due to a temporary perturbation or a loss of attention (Cuijpers et al., 2015). Indeed, various studies show that the degree of attention affects the stability of interpersonal coordination (e.g., Richardson et al., 2007; Temprado & Laurent, 2004).

Surge velocity fluctuations and race time

We verified that antiphase rowing indeed reduces within-cycle velocity fluctuations, which theoretically reduces power losses due to drag in comparison to in-phase rowing (Brearly et al., 1998; Hill & Fahrig, 2009; Hofmijster et al., 2007). Theoretically, the reduction in surge velocity fluctuations is optimised when the rowers move in antiphase relation (i.e., nulling their combined centre of mass displacement with respect to the boat). However, as the recover lasts longer than the drive phase, especially at lower stroke rates (Hill, 2002), it may be challenging to attune the drive to the recovery phase of a crew member and vice versa if both phases differ in duration, especially at 20 *spm*, which is also supported by the findings that crew coordination was less variable and more accurate for both in- and antiphase at 30 compared to 20 *spm*. Indeed, the reduced surge velocity fluctuations for antiphase were especially pronounced at 30 *spm*, which further supports that on-water antiphase rowing becomes more beneficial when rowing at higher (racing) stroke rates (Cuijpers & De Poel, 2017). The difference in drive and recover duration is less of an issue for in-phase crew coordination as here the rowers match their drive (and recovery) phases with one and other. Indeed, drive-recover ratio was closer to 1 (indicating that the drive (i.e., the propulsive) phase and recover phase are exactly equal in duration) in antiphase compared to in-phase crew coordination at 20 *spm*, which suggests that rowers compensate for the mismatch between drive and recovery duration by shortening the recovery-phase with respect to the drive phase at 20 *spm*.

Although rowing in antiphase resulted in a reduction in surge velocity fluctuations, rowing in antiphase did not (yet?) result in faster racing times compared to in-phase coordination. Nevertheless, one of the pairs (of which the rowers both rowed at World Cup level) managed to row only 4 *s* slower in anti- compared to in-phase at 30 *spm*. This is a very small difference, given that this is the very first time for them to row in antiphase.

Future directions

In the current experiment, rowers were able to row in antiphase coordination even though it was their very first time. As the results obtained here provide a positive indication, it would be interesting to study whether rowers can improve crew coordination by practicing the antiphase pattern and to which degree. For instance, will rowers be able to perform the antiphase pattern so accurately that drive and recovery perfectly align, which theoretically would optimise the reduction of velocity fluctuations? Practicing antiphase crew coordination may not only improve the quality of antiphase crew coordination, but may benefit in-phase crew coordination as well, as practicing movements in different movement patterns may improve motor performance in general (e.g., Frank, Michelbrink, Beckmann, & Schöllhorn, 2008). Apart from the question to which degree rowers that are experienced rowing in in-phase may improve and benefit from practicing antiphase rowing, another interesting additional step could be to split a group of novel rowers into two groups and teach one group to row in in- and the other group to row in antiphase coordination. In that way, the comparison between in- and antiphase coordination would not be corroborated by the extensive experience the rowers have rowing in in-phase coordination.

When rowing in in-phase, the boat is at a relatively low velocity when the rowers start the drive phase and the rowers accelerate the boat to a high velocity throughout the drive (Hill & Fahrig, 2009). In antiphase, however, the velocity of the boat remains more constant throughout the cycle, as verified by our results. This means that (relative to in-phase rowing) the boat is at a higher velocity in the beginning of the drive phase and at a lower velocity at the end of the drive phase. Indeed, some of the rowers informally indicated after their experimental trials that while rowing in antiphase they experienced a relatively (i.e., in comparison to in-phase rowing) lower pressure on the blades at the start of the drive and relatively higher pressure on the blades at the end of the drive phase. Together, this suggests that rowing in antiphase is not just a matter of changing the timing or phasing of the drive and recovery phase with respect to the other rower(s), but also changes the coordination (e.g., in terms of force application) of the individual rowing movement itself, which has also been found in other coordination dynamics tasks (e.g., Nordham, Tognoli, Fuchs, & Kelso, 2018). The latter also suggests that rowing technique may need to be optimised for antiphase rowing, e.g., by reducing surge velocity fluctuations even further by improving coordinative accuracy.

In a similar vein, the design and rigging (i.e., the ‘settings’ of the boat such as oar length) may need to be optimised to account for the changes in boat velocity and distribution of power throughout the rowing cycle when rowing in antiphase. A next logical step therefore would be to further investigate the effect of rowing in antiphase on the force profiles of the rowers measuring power production with force measurements on the blade and footboard, although measuring power on the water remains a challenge (see Lintmeijer, Hofmijster, Schulte Fischedick, Zijlstra, & Van Soest (2018); Hofmijster, Lintmeijer, Beek, & Van Soest, 2018). More insight into the biomechanics of antiphase rowing, such as into the difference in hydrodynamics around the blades and the change in air resistance in comparison to in-phase rowing may attribute to find out if rowing in antiphase can truly faster than rowing in in-phase (or not).

Ultimately, if one was to build a special boat, an eight would probably be the preferred boat class to test the antiphase rowing competitively. To be able to row in antiphase, rowers need more space between their seats for the oars not to collide. In the current experiment, we used a four-person boat for a double two crew (i.e., two persons handling two oars each) to provide this space. Of course, the boat we used is optimised for a crew of four rowers and is rather heavy (52 instead of 27 *kg*) to be moved by only two rowers. In the case of an eight, the crew would be divided into two groups of four rowing in antiphase with each other. This would mean that one would only need 70 *cm* extra to provide enough space for the oars not to collide (see also De Brouwer et al., 2013). In an eight, each rower handles one oar 'saves' an extra seat of space between the two subgroups. Since nowadays, boats can be built under minimum weight (and then precisely brought to minimum weight using lead strips), adding 70 *cm* to a 1990 *cm* boat can probably be achieved at minimum weight.

Although it may seem counterintuitive at first, rowing in antiphase in fact falls within the boundaries of the regulations of the International Rowing Federation (FISA). Rowing in antiphase is a change of technique, not an innovation in equipment. The slightly longer boat to provide space for the oars is not in contradiction to the regulations that require a minimum and not a maximum boat length, stating that "The minimum overall length of a racing boat shall be 7.20 metres." (FISA Rulebook 2018, p. 60). For now, it seems allowed to row competitively in antiphase, but whether this will remain the case, or whether the technique will be banned like the sliding rigger in the 1980's, only time will tell.

Conclusions

This study provides promising results for antiphase rowing on-water: most pairs were able to row in antiphase on the water, even though it was the very first time they performed it. Rowing in antiphase indeed reduced velocity fluctuations of the boat in comparison to in-phase rowing and this reduction was even more pronounced at 30 *spm*, which implies that antiphase rowing may indeed be mechanically more efficient, especially at high racing pace. In the present experiment, rowing in antiphase did not result in faster racing times. Nevertheless, given the potency to improve antiphase rowing through practice and optimisation of the design and rigging of the boat, these results provide a promising first indication of the benefits of antiphase rowing on water. More broadly, while crew rowing is often quoted as the archetypical example of synchronicity in team work, the results illustrate how complementarity, rather than perfect synchrony, may potentially be more beneficial for group performance.

Acknowledgements

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Supplementary materials

Table 1. Participant characteristics.

Pair	Position	Gender	Age (years)	Category[a]	Height (m)	Weight (kg)	Rowing experience (years)
1	Stroke	M	21	HM	1.97	84.8	6
1	Bow	M	23	HM	1.98	85.9	5
2	Stroke	M	21	LM	1.86	78.3	9
2	Bow	M	24	LM	1.83	69.9	8
3	Stroke	F	20	LW	1.73	64.5	1
3	Bow	F	20	LW	1.70	57.6	2
4	Stroke	M	23	LM	1.78	70.7	2
4	Bow	M	21	LM	1.78	75.6	3
5	Stroke	F	20	HW	1.8	75.2	2
5	Bow	F	24	HW	1.72	84.4	6
6	Stroke	M	27	LM	1.85	70.7	18
6	Bow	M	26	LM	1.91	79.3	4
7	Stroke	F	37	HW	1.81	73.0	13
7	Bow	F	35	HW	1.74	60.8	10
8	Stroke	M	22	HM	1.95	90.9	3
8	Bow	M	21	HM	1.98	100.1	3
9	Stroke	F	18	HW	1.76	70.9	5
9	Bow	F	18	HW	1.80	70.9	6

[b] H = open weight class, L = lightweight class, M = male, F = female.

Table 2. Rigging and specifications of the boat and oars.

Boat	
Name:	Gyasterix (2002)
Type:	Hudson C4.31 Classic 4-/X
Weight[1]:	44.0 kg
Weight range rowers:	75-88 kg
Oars	
Type:	Croker S4
Rigging	
Span:	1.60 m
Oar Length:	2.88 m
Inboard:	0.88 m
Oar Angle:	+ 4 °

[1] As used in the experiment, i.e., including the measurement system and two riggers.

Table 3. Means and standard errors of coordinative, boat, and heart rate measures for different conditions.

Pattern	*In-phase*				*Antiphase*			
Stroke Rate	*20 spm*		*30 spm*		*20 spm*		*30 spm*	
Dependent Measure	*mean*	*SE*	*mean*	*SE*	*mean*	*SE*	*mean*	*SE*
SD DRP catch BB (°)	*3.41*	*0.67*	*2.61*	*0.20*	*7.73*	*0.86*	*4.84*	*0.52*
SD DRP finish BB (°)	*4.81*	*0.87*	*3.01*	*0.40*	*10.89*	*1.15*	*6.55*	*0.92*
SD DRP catch SB (°)	*3.45*	*0.78*	*2.70*	*0.23*	*7.37*	*0.89*	*4.99*	*0.61*
SD DRP finish SB (°)	*4.28*	*0.60*	*3.49*	*0.27*	*11.64*	*0.75*	*6.94*	*0.76*
AE DRP catch BB (°)	*6.79*	*2.29*	*6.55*	*1.91*	*10.65*	*1.63*	*9.01*	*1.42*
AE DRP finish BB (°)	*6.48*	*0.69*	*7.27*	*1.95*	*11.03*	*1.48*	*13.30*	*2.32*
AE DRP catch SB (°)	*5.31*	*2.09*	*5.31*	*1.53*	*8.60*	*1.64*	*10.12*	*2.06*
AE DRP finish SB (°)	*9.69*	*1.63*	*9.79*	*2.86*	*11.77*	*1.14*	*12.61*	*1.87*
ratio	*0.69*	*0.03*	*0.98*	*0.02*	*0.74*	*0.02*	*0.95*	*0.04*
stroke rate (spm)	*19.97*	*0.26*	*28.44*	*0.26*	*20.66*	*0.13*	*28.40*	*0.09*
SD surge (m/s^2)	*1.58*	*0.11*	*2.46*	*0.15*	*1.28*	*0.08*	*1.77*	*0.14*
SD heave (m/s^2)	*0.43*	*0.03*	*0.60*	*0.02*	*0.42*	*0.02*	*0.61*	*0.02*
SD pitch (°/s)	*0.36*	*0.02*	*0.46*	*0.04*	*0.37*	*0.05*	*0.61*	*0.12*
SD roll (°/s)	*3.30*	*0.16*	*3.59*	*0.34*	*3.13*	*0.22*	*3.49*	*0.34*
time (s)	*263.00*	*8.09*	*235.00*	*8.14*	*276.80*	*7.43*	*247.60*	*9.55*
mean HF stroke (bpm)[a]	*161.28*	*7.46*	*178.61*	*1.83*	*152.38*	*4.97*	*175.40*	*2.60*
mean HF bow (bpm)[b]	*171.67*	*7.39*	*181.78*	*6.80*	*162.02*	*11.28*	*178.59*	*8.54*

[a] based on 4 pairs; [b] based on 3 pairs.