Coordination dynamics in crew rowing

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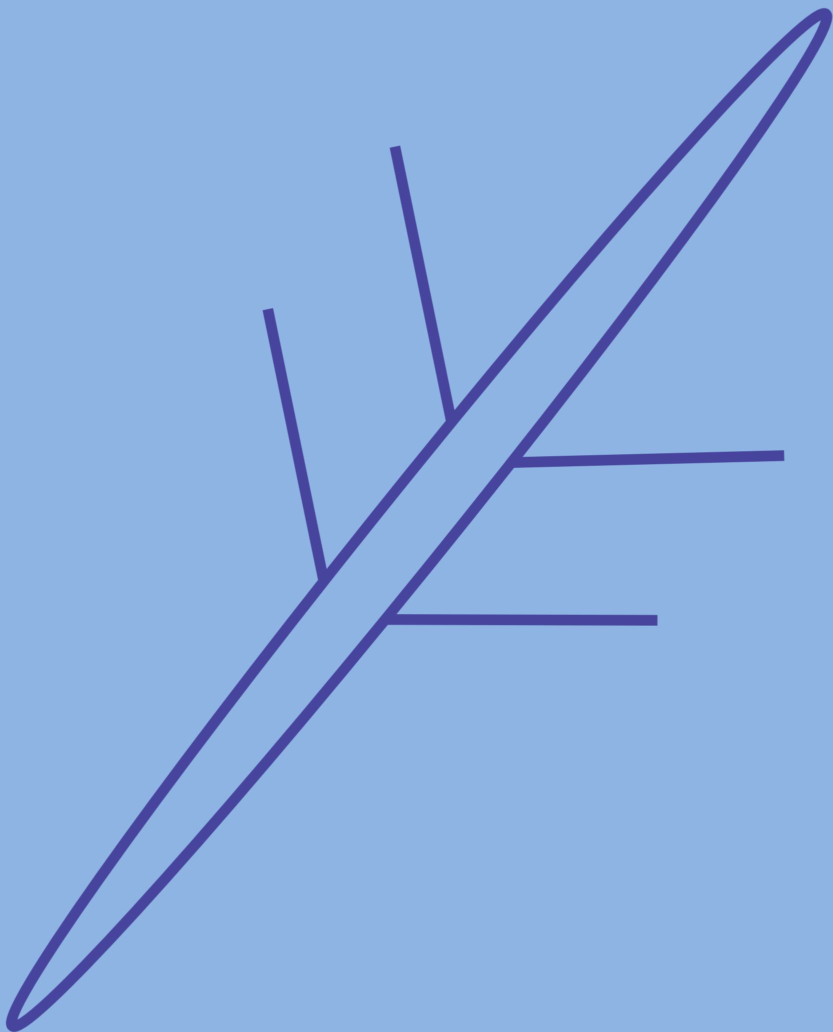
Rocking the boat: does perfect crew synchronisation reduce detrimental boat movements?

Chapter 3



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Abstract

In crew rowing, crew members need to mutually synchronise their movements to achieve optimal crew performance. Intuitively, poor crew coordination is often deemed to involve additional boat movements such as surge velocity fluctuations, heave, pitch and roll, which would imply lower efficiency (e.g., due to increased hydrodynamic drag). The aim of this study was to investigate this alleged relation between crew coordination and boat movements at different stroke rates. Fifteen crews of two rowers rowed in a double scull (i.e., a two-person boat) at 18, 22, 26, 30 and 34 strokes per minute. Oar angles (using potentiometers) and movements of the boat (using a three-axial accelerometer-gyroscope sensor) were measured (200 *Hz*). Results indicated that crew synchronisation became *more* consistent with stroke rate, while surge, heave and pitch fluctuations *in*creased. Further, within each stroke rate condition better crew synchronisation was related to less roll of the boat, but *in*creased fluctuations regarding surge, heave and pitch. Together this demonstrates that while better crew synchronisation relates to enhanced lateral stability of the boat, it inevitably involves *more* detrimental boat movements and hence involves *lower* biomechanical efficiency.

Introduction

In competitive rowing, a crew has to maintain the highest possible velocity over the course of the race in order to win. However, the velocity of the boat does not remain constant, but fluctuates within the rowing cycle (Hill & Fahrig, 2009), which is related to the fact that the rowing stroke cyclic comprises two phases: the drive and the recover. The drive starts with the 'catch' placing the blades into the water, after which the rowers of a crew collectively push off against the water in order to propel the boat. After the drive, the blades leave the water ('finish') and the rowers return towards their initial catching position ('recover'). As a result of this discontinuous propulsion and displacement of the crews' centre of mass relative to the boat, the velocity of the boat fluctuates within the rowing cycle, entailing a power loss of 5-10% (Sanderson & Martindale, 1986). As the power to overcome hydrodynamic drag is related to the velocity of the shell cubed, theoretically, reducing these surge velocity fluctuations would increase efficiency (Brearly, De Mestre, & Watson, 1998; Hill & Fahrig, 2009; Hofmijster, Landman, Smith, & Van Soest, 2007; Martin & Bernfield, 1980).

For crew rowing, the coaching literature (e.g., O'Brien, 2011) and also scientific research (e.g., Wing & Woodburn, 1995), deem that in order to minimise detrimental boat movements a crew must row in perfect synchrony. Differences in amplitude or timing of force application during the drive may result in net torques around the centre of the boat, entailing additional movements, such as surge, yaw, pitch and roll (cf., Barrow, 2010; Hill & Fahrig, 2009; Wing & Woodburn, 1995, see Figure 1). Such additional boat movements may entail more hydrodynamic drag and thus impede net boat velocity (Baudouin & Hawkins, 2002). Vice versa, such additional movements of the boat may also perturb crew coordination. As such, the degree of mutual synchronisation of the crew is regarded as an important determinant for optimal performance. In the present study, we examine the relation between the degree of crew synchronisation and movements of the boat at different stroke rates.

Crew rowing

Many studies have considered the effect of the movements of a single rower on boat movements (e.g., Baudouin & Hawkins, 2002; Sanderson & Martindale, 1986; Soper & Hume, 2004), however in the case of crew rowing, it is the *collective* performance of the crew that affects the movements of the boat (e.g., Baudouin & Hawkins, 2004; De Poel, De Brouwer, & Cuijpers, 2016; Hill, 2002; Wing & Woodburn, 1995). There is some indication that crew synchronisation varies within the stroke cycle. For six elite coxless fours, Hill (2002) showed that the difference in timing of the catch between the rowers (14.2 *ms* at

23-25 *spm* and 11.2 *ms* at 31-41 *spm*) decreased in comparison with the finish (25.8 *ms* at 23-25 *spm* and 21.7 *ms* at 31-41 *spm*). These differences in timing between rowers became smaller at higher stroke rates, which suggested that crew coordination around the catch and finish enhances with increasing stroke rate. Note, however, that a higher stroke rate implies a shorter cycle duration. As such, the observed decrease in timing difference might result from a shorter stroke duration. This requires crew synchronisation to not only be expressed and analysed in units of absolute time but also in units of cycle.

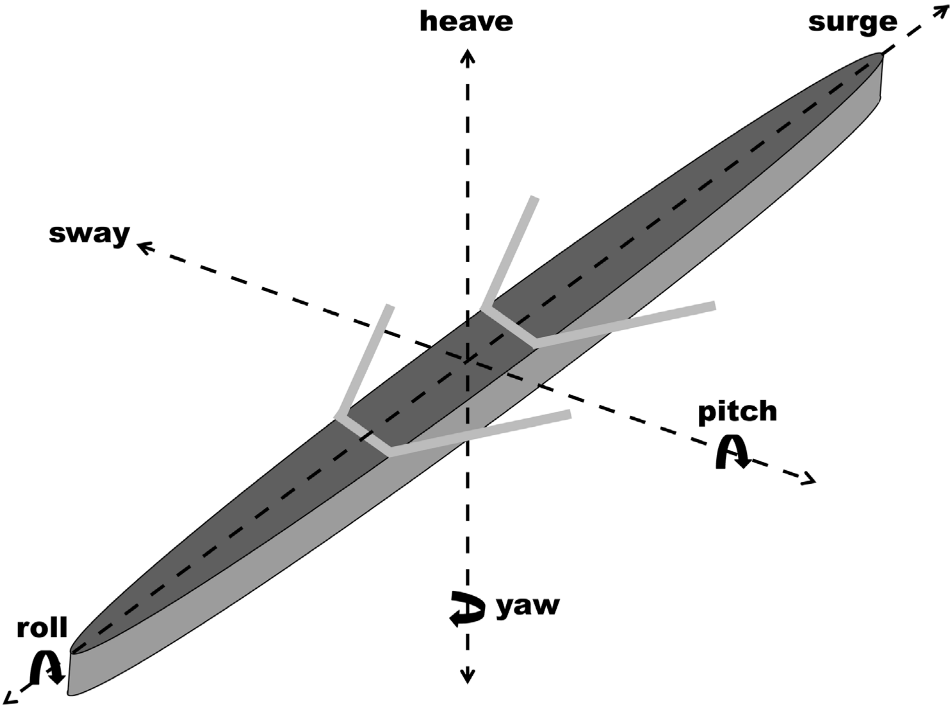

Figure 1. Movements of the boat. Most important in sculling (i.e., each rower is handling two oars) are surge (forward-backward), heave (up-down), roll (sideway turning) and pitch (dipping of the bow into the water).

Coordination dynamics

Inspired by studies on interpersonal coordination dynamics, for a crew of two rowers, crew coordination can be expressed in terms of relative phase (ϕ):

$$\phi = \theta_2 - \theta_1 \qquad \text{(Eq. 3.1)}$$

with ϑ_1 and ϑ_2 depicting the phase angle of (the movements of) each rower. The phase angle reflects for each point in time in which phase of the movement cycle (from 0° to 360°) each rower resides. Alternatively, the relative phase can also be determined based on a discrete point within the cycle, such as based on the moments of the catch or finish (see Equation 3 below). These measures depict the synchronisation of the rowers' movements: a relative phase value of 0° indicates no difference in phase angle between the rowers and thus perfect synchronisation. The variability of relative phase serves as an indicator of the consistency of crew coordination (Cuijpers, Zaal, & De Poel, 2015; De Brouwer, De Poel, & Hofmijster, 2013; De Poel et al., 2016). A small amount of variation in relative phase indicates a more stable coordination, which is more resilient to perturbations (Haken, Kelso, & Bunz, 1985; Schmidt, Carello, & Turvey, 1990), such as due to internal (e.g., temporary loss of attention) or external (e.g., turbulent water conditions) sources of noise.

Rowing studies have shown that an increase in stroke rate and associated increase in boat velocity inevitably enlarge boat velocity fluctuations (Hofmijster et al., 2007; Martin & Bernfield, 1980; Hill & Fahrig, 2009). A similar argument holds for heave and pitch fluctuations (for more details, see 'Discussion'). Next to the increase in boat movements, an increase in movement frequency also decreases the stability of coordination (Haken et al., 1985; Kelso, Scholz, & Schöner, 1986; Schmidt et al., 1990). Thus, on top of the increased surge, heave, and pitch fluctuations, higher stroke rates are expected to involve *poorer* crew synchronisation, which would impede performance even further as this could imply additional detrimental movements of the boat (Wing & Woodburn, 1995). Though recent research on coupled ergometers indicated no effect of stroke rate on consistency of crew coordination for stroke rates between 30 and 36 *spm* (Cuijpers et al., 2015), it remains to be investigated whether these results hold for 1) stroke rates below 30 *spm*, and 2) rowing on water. The aim of this research is therefore to investigate the relation between the consistency of crew coordination and boat movements (in terms of surge, heave, pitch and roll fluctuations) at different stroke rates.

Method

Participants

Twenty-seven rowers participated in the experiment (3 women, 24 men; mean age 20, SD 7 years; mean body height 1.76 ± SD 0.06 *m*; mean body mass 66 ± SD 15 *kg*; mean rowing experience at competitive level 7 ± SD 6 years; mean training load 11 ± SD 3 hours per week), which were paired into 15 combinations. Three of the 27 rowers rowed in two different combinations. To allow for sufficient variation in degree of crew synchronisation, crews differing in rowing experience were included, varying from combinations that rowed together internationally for several years to crews that had only rowed together a few times before. Note however that only rowers with at least one year experience in national competition were included. For more detailed information on the different combinations, see Table 1 in Supplementary Materials. Participants (or in case of junior rowers, their parents) provided written informed consent. The Ethics Committee of the Faculty of Human Kinetics, University of Lisbon approved the study that was conducted according to the principles expressed in the Declaration of Helsinki.

Experimental setup

Trials were performed in a double scull (i.e., two-persons rowing boat, in which each rower is handling two oars). The horizontal angles of the port (right) oars, reflecting the stroke movements of both rowers, were measured using potentiometers (Bourns, 6639 Precision Potentiometer). 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.) placed in a waterproof housing secured to the boat behind the bow rower (i.e., in direction of the bow of the boat). The outputs of these different sensors were sampled on a microcontroller (Olimexino-328) at 200 *Hz* and written onto a SD-card within the waterproof housing. Longitude and latitude of the boat was registered separately using a GPS tracker (Time Team Regatta Systems, sampling rate: 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*). Crews rowed at respectively 18, 22, 26, 30 and 34 *spm* for 2 *min* each. At the start, after the 26 *spm* bin 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 stroke rower (i.e., the rower crossing the finish last) received realtime 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). For each stroke rate condition, a 2 *min* bin was determined. Because the sample frequency slightly fluctuated around 200 *Hz*, the time series were interpolated using a piecewise cubic smoothing spline and then resampled at 200 *Hz*. The time series were then 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., Sabatini, Martelloni, Scapellato, & Cavallo, 2005). After this, the sensor values in *mV* were converted into oar angle (°), linear acceleration (m/s^2) and angular velocity (°/*s*). For further analysis, for all crews steady state bins of 30 cycles were determined for each stroke rate condition (see below).

Relative phase

The instantaneous spatio-temporal relation between the rowers' oar angles was expressed by the continuous relative phase (ϕ, Eq. 3.1). Because the drive and recover are generally not equal in duration (especially at lower stroke rates, Cuijpers et al., 2015; Hill, 2002; Martin & Bernfield, 1980), the angular velocity of the oar angle was normalised by the angular frequency calculated per half cycle following Varlet & Richardson (2011; for similar half-cycle normalisation procedures, see De Poel, Peper, & Beek, 2006; 2007). Start and end of each half cycle were based on the instances of the minimum and maximum excursions of the signal, which were determined using a custom made peak-picking algorithm. As such, the continuous phase angle was calculated for each rower with subscript *i* depicting the bow (1) and stroke rower (2), using:

$$\theta_i(t) = \tan^{-1}\frac{v_i(t)}{x_i(t)} \qquad \text{(Eq. 3.2)}$$

with x_i indicating the oar angle and v_i the normalised angular velocity of the oar. From these phase angles, the continuous relative phase ϕ *(t)* was determined according to Equation 3.1. Especially at lower stroke rates the stroke cycle deviates from perfect harmonicity (Cuijpers et al., 2015; De Brouwer et al., 2013). Therefore we also determined a discrete measure of relative phase based on point-estimates of oar angle extrema near the catch and finish of the stroke, which was calculated for each full cycle as:

in which $t_{1,j}$ and $t_{2,j}$ indicate the time of the j^{th} peak of the oar angle of rower 1 and 2. Note that other studies determined the catch and finish based on force data in which $t_{1,j}$ and $t_{2,j}$ indicate the time of the j^{th} peak of the oar angle of rower 1 and 2. Note that other studies determined the catch and finish based on force data (e.g., Hill, 2002; Wing & Woodburn, 1995). Although the extrema of the oar angle timeseries do not necessarily coincide with the onset and offset of force, they inform similarly about synchronicity between rowers' strokes (see also Sève, Nordez, Poizat, & Saury, 2011).

Dependent measures

The time series were analysed over steady state bins (30 *cyles*) for each stroke rate condition. These bins were selected based on visual inspection of stroke rate time series. A change from one stroke rate to another involves a transient stage, which in some cases lasted longer than in other cases. Therefore, the bins could only be determined a posteriori. For each tempo bin, mean absolute error (*AE*) of both continuous ($AE\phi$) and discrete relative phase (i.e. $AE\phi_{catch}$ and $AE\phi_{finish}$, for catch and finish respectively) and standard deviations (*SD*) of discrete relative phase (i.e. $SD\phi_{catch}$ and $SD\phi_{finish}$, for catch and finish respectively) were calculated as measures of coordinative performance using directional statistics (Mardia, 1972). Additional to the phase difference (ϕ, in °) between stroke and bow rower, *AE* and *SD* of the difference in timing (Δt, in *ms*) around catch and finish were determined, yielding $AE\Delta t_{catch}$, $SD\Delta t_{catch}$, $AE\Delta t_{finish}$, and $SD\Delta t_{finish}$.

Note that we only report boat movements that are related to the degree of crew coordination. For instance, in sculling both rowers handle two oars, which allows correcting for yawing individually (i.e., they do not need to coordinate their movements *together* to make the boat run straight). Furthermore, boat movements in terms of sway are unlikely to occur (if any, due to wind or current, rather than affected by crew coordination). Therefore, only the fluctuations (expressed in standard deviations) of surge and heave (based on the accelerometer timeseries) and pitch and roll (based on the gyroscope timeseries; see Figure 1), as represented by *SDsurge, SDheave, SDpitch* and *SDroll* are reported.

To determine average boat velocity in each stroke rate bin, for each point in time (*t*) boat velocity was calculated as the distance between the boat positions (i.e., longitude and latitude, see Sinnott; 1984) at two different time intervals (*t-7* and *t+7*, i.e. 15 samples) divided by the time it took to cover that distance (15 *s*). This procedure comes down to calculating the moving average with a window of 15 samples and was carried out to smoothen the within cycle velocity fluctuations. Finally, the thus obtained boat velocity was averaged over 1 *min* for each tempo bin.

Statistical analysis

Each of the above mentioned dependent measures was subjected to a 5 Tempo (18, 22, 26, 30 and 34 *spm*) repeated measures ANOVA. If the assumption of sphericity was violated, the degrees of freedom were adjusted using a Greenhouse-Geisser procedure. An α of 0.05 was adopted for all tests of significance. If necessary, Tempo effects were further scrutinised via post hoc paired samples *t*-tests (using a modified Bonferroni α-level correction procedure that takes the correlation between conditions into account; see Uitenbroek, 1997).

Results

Crew coordination

All coordinative measures were significantly affected by stroke rate (see Table 1). Measures of crew coordination variability ($SD\phi_{PE\text{-}catch}$, $SD\phi_{PE\text{-}finish}$, $SD\Delta t_{catch}$ and $SD\Delta t_{finish}$) decreased with an increase in stroke rate (Figure 2, left panel). Post hoc analysis revealed that for $SD\phi_{PE\text{-}catch}$, mean values in 26 and 30 *spm* were significantly lower than in 18 and 22 *spm* and $SD\phi_{PE\text{-}finish}$ was significantly lower in 30 compared to 18 *spm*. For $SD\Delta t_{catch}$ all stroke rate levels differed significantly from each other, except for 18 and 22 *spm* and 30 and 34 *spm*. For $SD\Delta t_{finish}$ all stroke rate levels differed significantly from each other, except for 22 and 26 *spm* and 30 and 34 *spm*.

Likewise, measures of crew coordination accuracy ($AE\phi$, $AE\phi_{PE\text{-}catch}$, $AE\Delta t_{catch}$ and $AE\Delta t_{finish}$) decreased at higher stroke rates, with one notable exception: $AE\phi_{PE\text{-}finish}$ significantly *in*creased with stroke rate (Figure 2, right panel). Note that an increase in $SD\phi_{(PE)}$ indicates a decrease in consistency of coordination and that an increase in $AE\phi_{(PE)}$ indicates a decrease in accuracy of coordination.

Post hoc analysis revealed that 18 *spm* significantly differed from 30 and 34 *spm* and 22 from 30 *spm* for $AE\phi$. For $AE\phi_{PE\text{-}catch}$ 18 *spm* differed significantly from 26 and 34 *spm* and for $AE\phi_{PE\text{-}finish}$ 26 *spm* differed significantly from 18 and 22 *spm*. For $AE\Delta t_{catch}$ all stroke rate levels differed significantly from each other except for 30 and 34 *spm*, and for $AE\Delta t_{finish}$ 30 *spm* differed significantly from 18, 22, and 26 *spm*. Note that in respectively Tempo 1 and 5 crews on average achieved a slightly higher/lower stroke rate than instructed.

Table 1. RM ANOVA results for crew coordination and drive-recovery ratio.

	F	*df, error*	*p*	η_p^2
$SD\phi_{PE\text{-}catch}$ (°) [a]	6.101	2.037, 28.514	<.01	.304
$SD\phi_{PE\text{-}finish}$ (°) [a]	3.779	1.672, 23.406	<.05	.213
$SD\Delta t_{catch}$ (ms) [a]	27.893	1.634, 22.878	<.001	.666
$SD\Delta t_{finish}$ (ms) [a]	16.444	1.304, 18.258	<.001	.540
$AE\phi$ (°)[a]	3.781	1.769, 24.763	<.01	.213
$AE\phi_{PE\text{-}catch}$ (°) [a]	4.992	2.390, 33.458	<.01	.263
$AE\phi_{PE\text{-}finish}$ (°)	3.025	4, 56	<.05	.178
$AE\Delta t_{catch}$ (ms) [a]	18.113	1.751, 24.510	<.001	.564
$AE\Delta t_{finish}$ (ms)	3.188	4, 56	<.05	.185

[a]Greenhouse-Geisser correction.

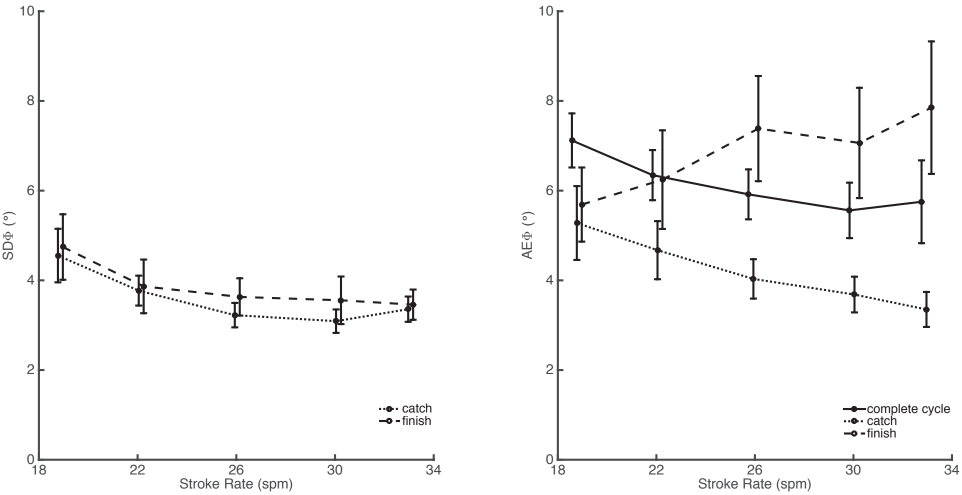

Figure 2. Variability around catch and finish (left panel) and accuracy of relative phase over the complete cycle and around catch and finish (right panel) at different stroke rates. Error bars represent standard errors. For mean values and standard errors, see Supplementary Materials, Table 2.

Boat Movements

SDsurge, SDheave, SDpitch and V_{boat} increased significantly with stroke rate, whereas *SDroll* was not affected by stroke rate (Table 2 and Figure 3). Post hoc analysis revealed significant differences between all stroke rate levels for *SDsurge* and *SDheave*. For *SDpitch* significant differences were found between all stroke rate levels, except between 22 and 26 *spm*. For *Vboat* all stroke rate levels significantly differed from each other except for 30 and 34 *spm*.

Table 2. RM ANOVA results for boat movements.

	F	*df, error*	*p*	η_p^2
SDsurge (m/s2) [a]	638.944	1.786, 25.000	<.001	.979
SDheave (m/s^2)	107.014	4, 56	<.001	.884
SDroll (°/s) [a]	1.984	2.310, 32.343	.148	.124
SDpitch (°/s) [a]	23.969	1.848, 25.869	<.001	.631
Vboat (m/s) [a]	78.947	1.570, 21.979	<.001	.849

[a] *Greenhouse-Geisser correction.*

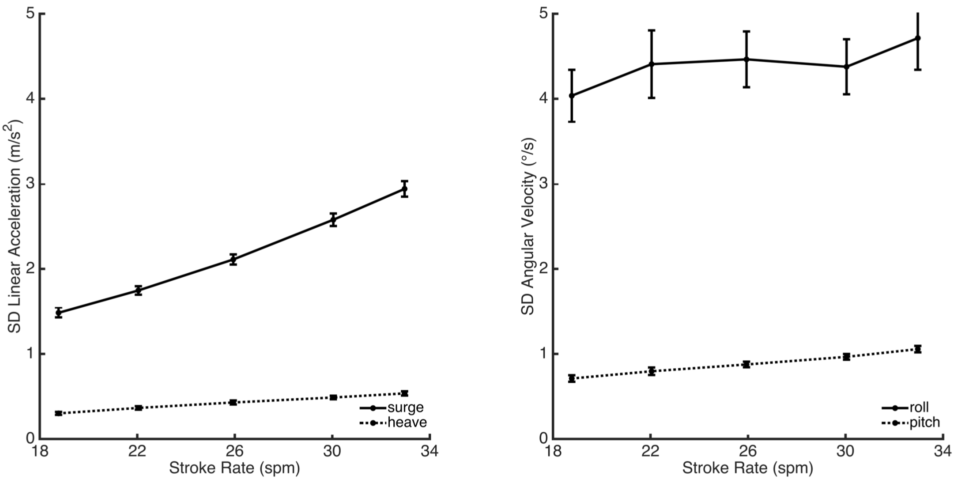

Figure 3. Variability of boat movements over different stroke rates. Error bars represent standard errors. For mean values and standard errors, see Supplementary Materials, Table 2.

Relation between crew coordination and boat movements

The correlation coefficients between $SD\phi_{PE\text{-}catch}$ and $SD\phi_{PE\text{-}finish}$ on the one hand and *SDsurge, SDheave, SDroll* and *SDpitch* on the other hand for each stroke rate are shown in Tables 3 and 4. A significant negative relation between $SD\phi_{PE\text{-}catch}$ and *SDsurge* was present at 18, 26 and 30 *spm*. At all stroke rates a significant positive relation between $SD\phi_{PE\text{-}catch}$ and *SDroll* was present. For $SD\phi_{PE\text{-}finish}$ a significant negative relation between $SD\phi_{PE\text{-}finish}$ and *SDheave* was present at 22, 26 and 34 *spm*. At stroke rates 26-34 *spm*, a positive relation between $SD\phi_{PE\text{-}finish}$ and *SDroll* was present. Although not all correlation coefficients of $SD\phi_{PE\text{-}catch}$ and $SD\phi_{PE\text{-}finish}$ reach significance, the correlation coefficients (*r*-values) suggest that, if any, a lower variability of relative phase around the catch and finish is related to an increase in surge, heave, and pitch variability. The correlation coefficients for *SDroll* though suggest a positive relation between $SD\phi_{PE\text{-}catch}/SD\phi_{PE\text{-}finish}$ and *SDroll*. Scatter plots of consistency of crew coordination at the catch and finish and surge, heave, roll and pitch variability for each crew at different stroke rates are shown in Figures 4 and 5. Note that, despite the intention to test the different crews in similar weather conditions, crews may have experienced different degrees of perturbations (e.g., due to waves) which may have affected roll variability between crews: a better crew (i.e., more resistant to perturbations) may still show less consistent coordination if exposed to more perturbations than a lesser crew. Given the small timeframe in which the different stroke rates were performed, we assume weather conditions not to have affected differences in crew coordination between different stroke rates *within* a crew.

Table 3. Correlation coefficients between $SD\varphi_{PE\text{-}catch}$ and surge, heave, roll, and pitch variability at different stroke rates.

	18 spm	*22 spm*	*26 spm*	*30 spm*	*34 spm*
SD surge (m/s^2)	-0.53*	-0.51	-0.68*	-0.56*	-0.41
SD heave (m/s^2)	-0.23	-0.45	-0.43	-0.43	-0.27
SD roll (°/s)	0.66*	0.55*	0.83*	0.76*	0.64*
SD pitch (°/s)	0.06	-0.23	-0.25	-0.45	-0.06

**Level of significance: $\alpha < .05$.*

Table 4. Correlation coefficients between SD$\varphi_{PE\text{-}finish}$ and surge, heave, roll, and pitch variability at different stroke rates.

	18 spm	*22 spm*	*26 spm*	*30 spm*	*34 spm*
SD surge (m/s^2)	-0.41	-0.44	-0.41	-0.50	-0.44
SD heave (m/s^2)	-0.38	-0.61*	-0.55*	-0.45	-0.63*
SD roll (°/s)	0.32	0.23	0.74*	0.57*	0.70*
SD pitch (°/s)	-0.08	-0.43	-0.18	-0.36	-0.24

Level of significance: $\alpha < .05$.

Discussion

The aim of this study was to investigate the relation between crew coordination and movements of the boat. Based on suggestions from rowing literature (Hill & Fahrig, 2009; Wing & Woodburn, 1995) we tested whether a more consistent crew coordination was associated with lower variability in boat movements (i.e., surge velocity fluctuations, heave, pitch and roll). Furthermore, the effect of stroke rate on both crew coordination and boat movements was studied (see also Cuijpers et al., 2015; Hill & Fahrig, 2009).

Crew coordination

Crew coordination around the catch and finish became more consistent with an increase in stroke rate. These results are not in line with coupled oscillator predictions, from which consistency of (interpersonal) coordination would be expected to *de*crease with an increase in movement frequency (Haken et al., 1985; Schmidt et al., 1990). Studies on interpersonal coordination suggest that there might be an optimum in movement frequency (i.e., preferred oscillation frequency) towards which coordinative variability decreases (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998). This would imply the consistency of crew coordination to decrease above, but also *below* a certain preferred stroke rate (De Poel et al., 2016). Indeed, in experiments on coupled ergometers, Cuijpers et al. (2015) found no compelling support for coordinative performance to change over stroke rates between 30 and 36 *spm*. The present results concur with this: consistency of crew coordination increased for the lower stroke rates (from 18 to 26 *spm*) but levelled at higher stroke rates (higher than 26 *spm*; see also Figure 2). As such, it might be that crew coordination consistency deteriorates when stroke rates are even higher. However, it is unlikely that rowers can increase stroke rates much further (for a discussion on this see Cuijpers et al., 2015).

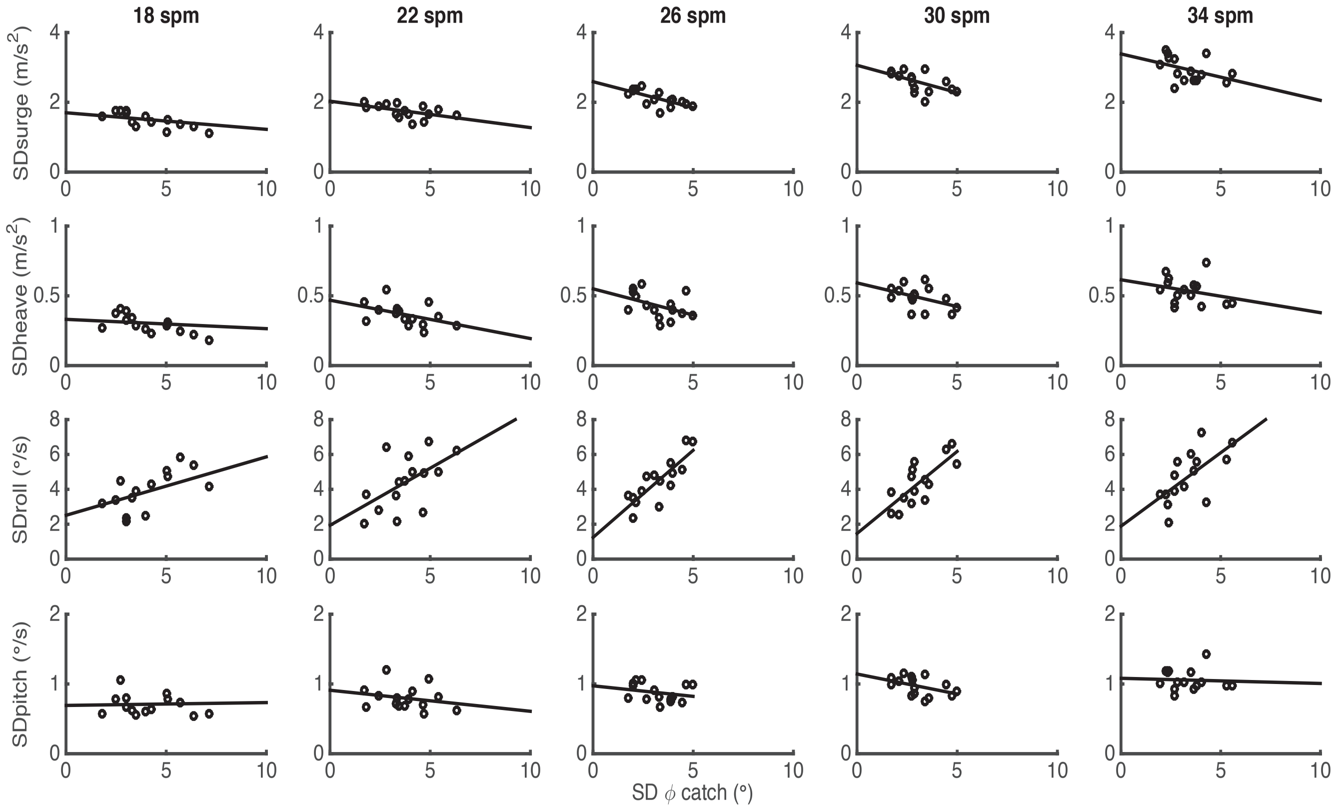

Figure 4. Relation between variability of crew coordination at the catch and variability of boat movements at different stroke rates.

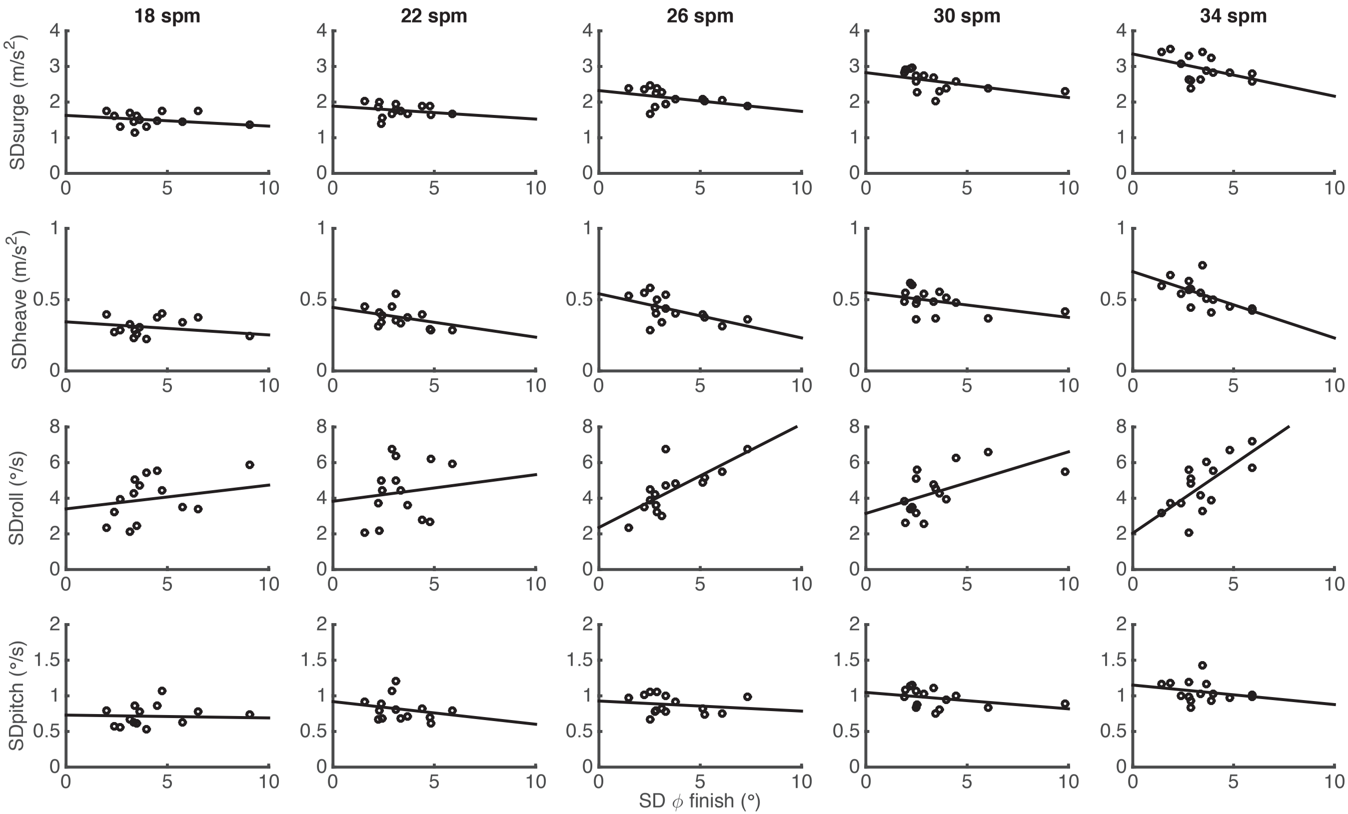

Figure 5. Relation between variability of crew coordination at the finish and variability of boat movements at different stroke rates.

The decrease in timing difference between rowers in both catch and finish over stroke rate in a study of Hill (2002) suggest crew coordination to become more accurate with increasing stroke rates. As stated in the 'Introduction', accuracy of crew coordination expressed in time may distort the effect of stroke rate, as cycle duration is not taken into account. Therefore, in the current study, accuracy of crew coordination was also calculated in terms of relative phase, thus taking cycle duration into account. Similar to Hill (2002), differences in timing around catch and finish decreased with stroke rate, with smaller differences around the catch than around the finish. In terms of relative phasing though, crew coordination over the complete cycle and around the catch became more accurate with stroke rate, whereas the finish became *less* accurate with stroke rate. From research in motor control it is known that the control of the movement cycle is often based on specific points within the cycle, also referred to as anchoring (Beek, 1989). In terms of rowing, it is obvious that the catch, and possibly the finish are candidates for anchor points. Given that anchor points are characterised by local reduction of variability (Roerdink, Ophoff, Peper, & Beek, 2008), the increase in accuracy around the catch and decrease in accuracy around the finish clearly indicate that control of the stroke cycle is primarily at the catch, especially at higher stroke rates.

Boat movements

While crew coordination became less variable at higher stroke rates (see Figure 2), the variability of boat movements in terms of surge, heave and pitch actually *in*creased (see Table 2 and Figure 3). Note however, that stroke rate and boat velocity highly covary (Hill & Fahrig, 2009). Indeed, in practice it is highly unlikely that an increase in stroke rate happens without an increase in boat velocity, since rowers would need to drastically decrease their power per stroke. As a consequence, it is difficult to statistically dissociate whether the observed increases in surge, heave and pitch are due to stroke rate, boat velocity, or both. As an example, surge velocity fluctuations are related to both. First, given an average boat velocity, a higher stroke rate also increases surge velocity fluctuations because relative to the rowers' bodies, the boat is moved to the same amount (leg length) in shorter time durations. Second, given a specific stroke rate, to be able to maintain a higher boat velocity rowers would have to accelerate the boat even further in order to compensate for the stronger deceleration encountered during the recovery phase, since hydrodynamic drag increases as a square function of the velocity of the shell (see Hill and Fahrig, 2009). Thus, a higher average boat velocity inevitably implies more surge velocity fluctuations. The observed increase in heave fluctuations at higher stroke rates/ boat velocity likely relate to increased force applied to the foot stretcher, as this force involves both a horizontal and a vertical component, yielding vertical oscillations (Kleshnev, 2016). Pitch is most likely due to the within-cycle mass displacement of the rowers relative to the boat, which clearly increases with stroke rate. In sum, the observed increases in surge velocity fluctuations, heave and pitch at higher stroke rates (hence higher boat velocity) are inevitable and not necessarily related to the quality of crew coordination.

Crew coordination related to boat movements

Contrary to expectations (see Introduction) within each stroke rate condition more consistent crews showed *more* boat movement fluctuations in terms of surge velocity, heave and pitch (reaching significance for crew coordination variability around the catch with surge variability at 18, 26 and 30 *spm* and for crew coordination variability around the finish with heave variability at 22, 26 and 34 *spm)*. From a mechanical point of view, this might be explained by the fact that a more synchronously moving crew implies a larger net mass-displacement of the crew with respect to boat (De Brouwer et al., 2013; Hill & Fahrig, 2009), involving an increase of surge velocity, heave, and pitch fluctuations. Note that adult (and hence possibly more experienced) crews are generally heavier than junior crews, which may contribute the negative correlation between crew coordination and in boat movements, particularly to pitch. Regarding lateral balance however, more consistent crews showed reduced roll of the boat, with significant effects for all stroke rates at the catch and at 26-34 *spm* at the finish. This indicates that poorer crew coordination may indeed impede lateral balance, as suggested by Wing & Woodburn (1995).

Perspectives

This study illustrates that better crew synchronisation relates to more movements of the boat in terms of surge, heave and pitch fluctuations. From this, one could infer that better synchronisation is less efficient. Now, does this mean that crews should not row in perfect synchrony? Evidently not: a decrease in efficiency does not necessarily equate a decrease in performance. Most likely, better coordination enables higher power production: a more stable crew coordination is less prone to perturbations and might as such enable the crew to maximise their collective power output.

Furthermore, this study stresses the importance of regarding (and analysing) the behaviour of the crew *as a whole*, and provides incentives for quantifying crew synchronisation processes (see also Sève et al., 2011). Given that on-water measurements systems become more and more commercially available, coaches can use similar methods for monitoring and training crew performance.

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Supplementary materials

Table 1. Participant characteristics and determination of crews.

Crew Nr.[a]	Position	Gender	Age (years)	Category[b]	Height (cm)	Weight (kg)	Experience (years)	Training load (hours/week)
1 (8)	Stroke	M	20	BM	187	83	5	13
1	Bow	M	18	BLM	174	67	2	13
2 (6)	Stroke	M	15	JM	175	63	3	8
2	Bow	M	15	JM	171	68	1	6
3	Stroke	M	16	JM	167	60	2	8
3	Bow	M	17	JM	171	59	3	8
4	Stroke	M	15	JM	179	71	8	12
4	Bow	M	15	JM	172	72	3	10
5	Stroke	F	19	BLW	175	58.5	6	12
5	Bow	F	19	BLW	163	51.4	6	12
6	Stroke	M	15	JM	182	-	4	5
6 (2)	Bow	M	15	JM	175	63	3	8
7	Stroke	M	-	Mas	-	-	-	-
7	Bow	M	46	Mas	170	83	10	10
8	Stroke	F	19	BW	160	65	5	12
8 (1)	Bow	M	20	BM	187	83	5	13
9	Stroke	M	23	LM	178	70	11	20
9	Bow	M	37	LM	180	70	20	12
10	Stroke	M	16	JM	183	70.5	3	8
10	Bow	M	16	JM	180	60	2	12
11	Stroke	M	17	JM	175	60	4	12
11	Bow	M	16	JM	176	59	4	12
12	Stroke	M	17	JM	186	74.5	7	10
12	Bow	M	19	BLM	182	74	9	14
13	Stroke	M	21	BLM	178	73	5	12
13	Bow	M	19	BLM	179	75	8	12
14 (15)	Stroke	M	31	LM	174	72	20	14
14	Bow	M	26	LM	175	71	10	12
15 (14)	Stroke	M	31	LM	174	72	20	14
15	Bow	M	31	LM	175	71	23	14

[a] *three rowers rowed in two combinations, the alternative combination is indicated between bracket;*
[b] *J= junior (<18 years), B = under 23 (<23 years), M = male, F = female, L = lightweight.*

Table 2. Means and standard errors of coordinative measures and boat movements at different stroke rates.

	18 spm		*22 spm*		*26 spm*		*30 spm*		*34 spm*	
	Mean	*SE*	*Mean*	*SE*	*Mean*	*SE*	*Mean*	*SE*	*Mean*	*SE*
stroke rate (spm)	18,59	0,06	21,89	0,29	25,86	0,13	29,91	0,18	33,18	0,25
AEϕ (°)	6,10	0,50	5,66	0,51	5,53	0,50	5,08	0,50	4,88	0,49
AEϕcatch (°)	3,92	0,64	4,09	0,71	3,73	0,47	3,59	0,55	2,75	0,37
AEϕfinish (°)	4,64	0,66	5,40	1,17	6,63	1,37	6,20	1,22	6,57	0,88
AEΔtc (ms)	35,24	5,81	30,90	5,24	24,12	3,09	19,97	3,01	13,84	1,90
AEΔtf (ms)	41,67	5,93	41,05	8,72	42,52	8,70	34,62	6,82	33,08	4,49
SDϕ (°)	5,24	0,31	4,80	0,36	4,58	0,35	3,91	0,33	4,00	0,32
SDϕcatch (°)	3,70	0,45	3,60	0,48	2,82	0,29	2,75	0,27	3,14	0,36
SDϕfinish (°)	3,59	0,41	3,11	0,37	2,93	0,32	2,66	0,24	2,99	0,32
SDΔtc (ms)	33,21	3,99	27,28	3,42	18,25	1,86	15,32	1,46	15,78	1,83
SDΔtf (ms)	32,34	3,73	23,87	2,93	18,88	1,99	14,90	1,30	15,16	1,58
SDsurge (m/s²)	1,54	0,07	1,80	0,07	2,18	0,08	2,66	0,10	3,07	0,12
SDheave (m/s²)	0,31	0,02	0,38	0,02	0,44	0,03	0,50	0,03	0,56	0,03
SDroll (°/s)	3,72	0,37	4,04	0,51	3,83	0,27	4,06	0,40	4,30	0,46
SDpitch (°/s)	0,72	0,05	0,81	0,05	0,88	0,04	0,99	0,04	1,09	0,05
mean boat velocity (m/s)	2,97	0,17	3,26	0,10	3,48	0,12	3,71	0,12	3,75	0,12