Coordination dynamics in crew rowing

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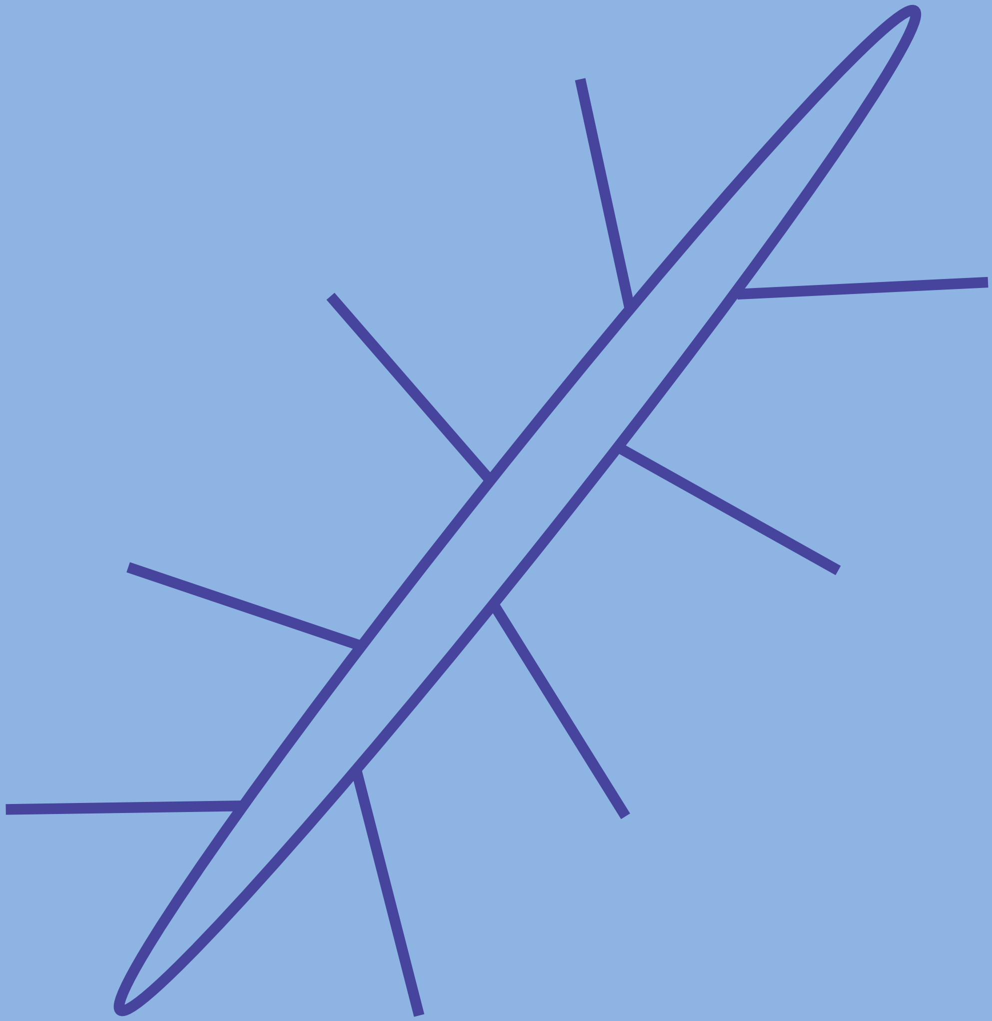
Crew rowing: an archetype of interpersonal coordination

Chapter 2



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Abstract

Crew rowing is often adopted as a pertinent example regarding synchronization of cyclical movements, as well as for inter-individual functional synergies and group processes in general. Given an extant nonlinear model of coupled oscillators, the theoretical perspective of coordination dynamics offers expedient tools for analysing between-rower interactions and their underpinnings. In this chapter, we therefore describe how coordination dynamics can be applied to crew rowing. We will discuss implications from (and for) coordination dynamics for rowing crew coordination regarding issues such as movement rate, different interpersonal coordination patterns, pattern switches (both intended and unintended), individual differences between the rowers (cf., detuning), and strength of coupling. These issues are illustrated and supported alongside previous studies on interpersonal coordination and crew rowing, as well as some recent results from on-water and off-water (pilot) experiments by our lab. Together this underwrites crew rowing as archetype of interpersonal coordination dynamics.

Introduction

Coordinating our actions with others is paramount in our daily lives. Between-person coordination is important for functional cooperative behaviour of a group of people, but also when the interaction between people is competitive. Regarding the group dynamics of a team of agents that has to cooperate (for instance cooperation with colleagues at work, or within a sports team), the behaviour of the multi-agent system as-a-whole emerges as a function of the cooperative interactions between the agents that constitute the system. For obvious reasons, team managers, coaches, etc., seek to optimize team performance as well as the performance of each individual within the context of that multi-agent system. In that respect, an often-used model of perfect within-team tuning is the rowing crew; managers often proclaim to members of their team that in order to achieve optimal (productive) performance their work efforts should be ideally synchronized, just like it works for a rowing crew. Also in scientific literature, crew rowing is often adopted as an archetypical, natural example to illustrate, explain and examine joint action, interpersonal coordination dynamics, and synchronization (e.g., Keller, 2008; Marsh, Richardson, & Schmidt, 2009; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007) and group processes in general as well (e.g., Ingham, Levinger, Graves, & Peckham, 1974; King & De Rond, 2011). Yet, as direct scientific examination of crew coordination is limited, it appears that the example of crew rowing is often adopted in a merely metaphorical manner.

To examine interpersonal interactions, the theoretical framework of coordination dynamics (for a general overview see, e.g., Kelso, 1995) offers expedient analysis tools. Using models of coupled oscillators, this approach is particularly well-suited for investigating cyclical movement behaviour. The cyclical nature of the rowing act, and the fact that it has to be performed in unity with others in the same boat, thereby offer crew rowing to be arguably one of the most relevant and exemplary real-life tasks concerning interpersonal coordination dynamics. Hence, inspired by studies of inter-personal coordination dynamics (e.g., Richardson et al., 2007), the purpose of the current chapter is to outline crew rowing within the pertinent theoretical framework of coordination dynamics, alongside some recent empirical work in this context. In doing so, we aim to demonstrate the expediency of coordination dynamics for crew rowing and vice versa. First, we briefly introduce the essentials of the sport of crew rowing and address previous studies that investigated crew coordination in rowing. Second, relevant concepts and issues in coordination dynamics will be elaborated on and then applied to crew rowing.

Crew Rowing

Rowers perform a cyclic movement pattern in which the legs, trunk, and arms partake in a synchronized fashion in the propulsion of the boat. Each rower is seated backwards in the boat and uses a single oar (sweep rowing) or two oars (sculling) to propel the boat. It is important to recognize that each stroke cycle consists of a propulsion phase (or drive) and a recovery phase. In the drive phase, a rower (sitting on a sliding seat) pushes off against the footboard (attached to the boat) using primarily the strong leg extensor muscles, while pulling on the oar(s) with the oar blade(s) in the water. At the 'finish' of the drive, the arms release the blade(s) from the water. In the recovery phase, the rower returns to the initial position by sliding forward on the seat with the blade(s) out of the water, to reposition the oar(s) for the next stroke. Then, at the so-called 'catch', the blade(s) enter(s) the water again so that a next stroke can be performed. As we will see later, the existence of a drive phase and a recovery phase and, accordingly, the movement of the rowers' center of mass relative to the boat due to the sliding seats, have a great influence on boat velocity.

In competitive rowing, the goal is to cover a course of 2000 meters as fast as possible, preferably faster than opponent crews. To achieve a high average boat velocity, maximizing power production is of course a prerequisite, while the crew also needs to minimize the power *losses*. In other words, rowers produce power to propel the boat via the oars, but at same time they want to lose as little as possible of the produced power to, for instance, slippage of the blades in the water. As such, a proper and fluent technique is required for efficient power application.

In crew rowing, even a team of individually strong and technically skilled rowers will probably not win races if they do not properly coordinate their movements with each other (O'Brien, 2011). Hence, they also have to develop an efficient 'crew technique'. Both in rowing practice and rowing science, mutual synchronization is generally regarded as a main determinant for optimal performance of a given crew (e.g., Hill, 2002; Wing & Woodburn, 1995). The overall idea is that when the crew is moving perfectly in sync, the power the rowers produce is optimally converted into forward velocity, mainly because it reduces unwanted boat movements (e.g., Hill & Fahrig, 2009). Indeed, if the overall forces at the blades are unbalanced and/or applied with imperfect mutual timing, this would cause net torques around the center of the boat, which entails dispensable rolling, yawing, and pitching of the boat (Baudouin & Hawkins, 2002). Poor synchrony would thus involve additional movements that disturb the balance of the boat, elongate the travelled distance of the boat, and create greater hydrodynamic drag.

Together, the general opinion of researchers and coaches is that to maximize average velocity, a crew must optimize their synchrony. The question arising then is how well do rowers in a boat synchronize? And how can we measure and analyse that? This knowledge could be very relevant for optimizing performance. Obviously, expert crews are expected to demonstrate better, more consistent synchronizing patterns than crews with less expertise. Besides, despite the well-known natural tendency for coupled systems towards synchronization (Kelso, 1995), it is also important to realize that rowing in sync does not simply come naturally. In fact, freshmen crews often need some months of training to achieve a common rhythm and require years of training to reach a desired expert level of synchronization. This calls for methods and concepts that allow for examination of such crew synchronization processes, and how this changes over time as a function of practice and other factors and interventions (e.g., crew member changes, boat velocity, etc.).

One way is to analyse the crew's synchronization from force measurements, for instance the force applied to the oars or blades over time. Although studies showed that rowers display an individually characteristic force-time pattern, varying the combination of rowers within a crew led the force-time profiles to be correlated with those produced by the other crew members, clearly indicating that rowers adjusted their behaviour to the crew (Baudouin & Hawkins, 2004; Hill, 2002; Wing & Woodburn, 1995). Furthermore, from force data of 180 successive strokes (at a stroke rate of about 18 strokes/min) for four rowers in an eight, Wing and Woodburn (1995) determined stroke onset times (i.e., catch) and saw that the degree of correspondence in catch timing between all four rowers was remarkably accurate, namely within a range of 10-20 ms. Furthermore, they analysed between-rower cross-correlations of peak forces, drive duration and recovery duration. Somewhat surprisingly, only the recovery durations positively correlated between rowers, while the drive durations did not, suggesting that crew synchronization varies within the stroke cycle. In line with this finding, based on force data, Hill (2002) found that timing differences between rowers in a boat (in this case coxless fours: crews of four sweep rowers without a coxswain) were generally smaller for the catch than for the finish for endurance intervals (at 23-25 *strokes/min*; 14.2 *ms* and 25.8 *ms*, respectively) and intensive intervals (at 31-41 *strokes/min*; 11.2 *ms* and 21.7 *ms*, respectively). In addition, this tentatively suggests that crew synchronization improved at higher stroke rates (see section '*Movement frequency*' for further discussion of the impact of stroke rate).

Another way is to analyse crew coordination based on movement data, such as trunk movement, oar angles, and/or displacement of the sliding seat. For instance, in a case study on a coxless pair with a self-indicated 'dysfunction of crew coordination', Sève, Nordez, Poizat, and Saury (2011) used the turning points in the oar angles to determine the onset differences between the rowers for each stroke. With such analysis, the authors were able to depict systematic differences in the interpersonal coordination of the catch times and entry angles of the oars, which allowed the pair's coaches to define new training objectives to remedy the imprecisions in the pair's coordination.

Apart from determining discrete features for each stroke, analysis of movement data implies that coordination can also be determined for the whole cycle and not solely for the drive phase, as is the case with force data. As such, an instantaneous and continuous measure of synchronization can be determined. Motivated from coordination dynamics, crew coordination can be displayed by the relative phase (ϕ) between rowers. In short, this measure depicts the difference between two rowers in terms of where they reside in their respective stroke cycle. If the relative phase equals zero, the rowers are exactly synchronous, whereas the amount of variation of the relative phase over time indicates the degree of consistency of crew coordination. Recently, this has been adopted in rowing experiments in the laboratory (De Brouwer, De Poel, & Hofmijster, 2013; Cuijpers, Zaal, & De Poel, 2015); Varlet Filippeschi, Ben-sadoun, Ratto, Marin, Ruffaldi, & Bardy, 2013) and on water (Cuijpers, Passos, Hoogerheide, Murgia, & De Poel, 2017). We will involve these studies in the discussion of coordination dynamics related to crew rowing, which will be done in the subsequent paragraphs.

Coordination dynamics and crew rowing

In general, coordination dynamics encompasses the study of coordinative patterns, that is, how patterns of coordination form, adapt, persist and change over time. This approach (e.g., Haken, Kelso, & Bunz, 1985; Kelso, 1995) offers an expedient framework for studying rhythmic coordination, in which the (in)stability of coordinative patterns is explained with reference to the coupling between the components that comprise the system. Most importantly for the purposes of the present chapter, it offers a well-established non-linear model of coupled oscillators, known as the Haken-Kelso-Bunz model, or HKB-model, that captures key properties and phenomena of isofrequency (i.e., identical movement rates) coordination (Haken et al., 1985). Although the HKB-model was originally developed for rhythmic bimanual coordination (i.e., within-person coordination), to date many studies have underwritten that between-person coordination abides by similar coordinative phenomena and principles (for reviews, see Schmidt, Fitzpatrick, Caron, & Mergeche, 2011; Schmidt & Richardson, 2008). Knowing this, crew rowing perfectly meets the conditions of this coupled oscillator model, in that it is a cyclical act of two (or more) coupled agents that are moving at equal movement rates. Moreover, the stroke cycles show behavior that is near to harmonic (i.e., sinusoidal). In the following sections, we will describe in a point by point fashion main predictions derived from the model, how these predictions are supported by previous empirical findings (or not), and how they may apply to crew rowing.

Differential pattern stability

In a seminal paper, Kelso (1984) demonstrated that while tapping fingers in an antiphase pattern (i.e., perfectly alternating, ϕ = 180°) an increase in movement frequency resulted in a spontaneous, involuntary transition towards in-phase coordination (i.e., perfectly coinciding, ϕ = 0°). However, when starting in in-phase coordination, no shift towards antiphase occurred. To account for this phenomenon, Haken et al. (1985) formulated a model of two non-linearly coupled limit cycle oscillators that constituted an equation of motion that could describe the rate of change in relative phase angle between the two oscillating components, following

$$\dot{\phi} = a \sin\phi - 2b\sin 2\phi \quad \text{(Eq. 2.1)}$$

with *a* affecting the attractor strength of in-phase coordination and *b* affecting the attractor strength of both in- and antiphase coordination. The ratio *b/a* is directly related to the movement frequency. Given Eq. 2.1, at low frequencies (i.e., *b/a* > .25) the model has two stable attractors, namely in-phase and antiphase, while other patterns are intrinsically unstable. Also for between-person tasks, the difference in stability for in-phase and antiphase coordination has been consistently demonstrated (for an overview, see Schmidt & Richardson, 2008).

This difference in the stability properties of coordinative patterns already poses the first challenge for crew rowing. At first glance this may seem a rather curious argument, since rowing crews only synchronize in an in-phase manner and other patterns are not and cannot be performed. However, perhaps somewhat surprisingly, the latter does not appear to be the case. That is, out-of-phase rowing *has* been considered in the past.

Rowing 90° out-of-phase

In fact, there is a long-standing ‘myth’ that out-of-phase crew rowing may be beneficial over the conventional in-phase crew coordination (see also *Steady-state antiphase crew rowing*). Around 1930, there have already been several actual attempts to row out-of-phase on water, also termed ‘syncopated rowing’ or ‘jazz rowing’. For instance, newspapers reported of British crews rowing in a four-phase strategy (ϕ = 90°; quarter-cycle-lag pattern) in an eight[4], and a three-

[4] Footage of these attempts is available via British Pathé: http://www.britishpathe.com/video/syncopated-rowing

phase strategy (ϕ = 120°; third-cycle-lag pattern) with a crew of six rowers. Although some reports conveyed that these attempts were successful, the syncopated boats received a lot of criticism. Stories mentioned that, after some training, the crews apparently managed to master the coordination, but this did not lead to sufficient gain in boat velocity and, more importantly, victories. In the end, the critics won and these try-outs were aborted, probably due to the fact that a sufficient gain in boat velocity was not achieved.

In hindsight, nowadays we know from coordination dynamics that 90° and 120° coordination patterns are intrinsically unstable patterns and, even after considerable practice, are extremely difficult to maintain, especially at higher movement rates. For bimanual coordination, support for this prediction has already been provided, for instance in experiments in which subjects practiced 90° interlimb patterns (e.g., Zanone & Kelso, 1992), while for between-person coordination to our knowledge no studies on learning new phase relations have been reported. Perhaps such studies might not exist because for two (or more) persons it is virtually impossible to (learn to) interact stably in a quarter cycle relation.

Therefore, we performed a single case experiment in which we had four experienced rowers row on ergometers (Concept2) that were positioned next to each other. The task was to row in a pace that was indicated by a sequence of beeps. The beeps had four different tone pitches that were presented in 90° phase delay with respect to each other. Each rower was assigned to one of the pitches and instructed to align the catches with the incidence of the beeps. Starting at a tempo of 20 strokes/min, each minute the tempo of the beeps was increased in steps of 2 strokes/min to a maximum of 32 strokes/min. Initially the rowers were able to maintain the 90° interpersonal pattern, but a breakdown of the pattern already occurred at 24 strokes/min. The breakdown involved a switch towards three rowers moving in in-phase relation, while the fourth rower was moving in antiphase relation to the other three. The subjects also performed a condition in which they were divided in two groups of two rowers. The two groups were instructed to row antiphase with respect to each other, while their pace was again indicated by beeps that increased in frequency. The rowers easily maintained the antiphase pattern until the end of the trial. This is not surprising, since the antiphase pattern is an intrinsically stable pattern. In subsequent studies, we therefore considered the stable antiphase pattern. In sum, it is likely that at high stroke rates stable 90° crew coordination is extremely difficult to achieve. Although after practice 90° out-of-phase patterns can be mastered (Zanone & Kelso, 1992), the stroke rates at which this pattern can be performed are limited and, hence, so is the velocity on water. As we will see, such problems exist to a much lesser extent for the antiphase pattern, because this is an intrinsically stable pattern.

Before we proceed, it is important to note that in ergometer rowing, rowers usually row on separate machines (as was also the case in the above experiment), whereas on water the rowers are linked in a mechanical way, since they share the same boat. We therefore subsequently performed a series of studies in which we analysed dyads of rowers in the lab using a two-ergometer system. This involves two ergometers that are put on so-called 'slides' (Concept2), so that they can move freely with respect to the ground, and which also allows them to be physically linked so that they move as one 'boat' (see De Brouwer et al., 2013; Cuijpers et al., 2015).

Steady-state antiphase crew rowing

Although, over the previous century, some thought that the idea behind out-of-phase crew rowing was that it would be faster because of more continuous propulsion (much like a car engine, where the pistons do not ignite at the same time but with a mutual phase delay), others already recognized that there is something else that mediates the potential velocity-gaining mechanism behind out-of-phase rowing. In rowing, 5 to 6% of the total power produced by the rower(s) is lost to velocity fluctuations of the shell within each rowing cycle. Shell velocity fluctuates because propulsion is not continuous (viz., the drive and recovery phase) and the relatively heavy rower(s), seated on their sliding seat, push off with the feet against the relatively light boat, causing the shell to decelerate during the drive and to accelerate during the recovery (Hill & Fahrig, 2009). As the power needed to overcome hydrodynamic drag is proportional to shell velocity cubed, minimizing velocity fluctuations of the boat while maintaining total power output will thus result in higher efficiency and hence, ceteris paribus, higher average boat velocity (see, e.g., De Brouwer et al., 2013; Hill & Fahrig, 2009).

Theoretically, in case of crew rowing, this can be achieved by rowing in antiphase coordination, a strategy in which two (groups of) rowers within the boat perform their strokes in perfect alternation (Brearly, De Mestre, & Watson, 1998; De Brouwer et al., 2013). In antiphase rowing, the movements of the rowers would almost perfectly counteract each other, resulting in a net center of mass movement (*CoM*) of the crew that stays close to the movement of the boat. As such, boat velocity would remain close to constant over the whole rowing cycle. A recent study confirmed for dyads rowing at 36 strokes/min on coupled ergometers (see above) that antiphase crew coordination is indeed mechanically more efficient, in that the power loss was reduced by 5% compared to in-phase rowing (De Brouwer et al., 2013). Importantly, the crews produced similar amounts of total power during in-phase and antiphase rowing, resulting in a 5% greater amount of useful power for antiphase coordination. Furthermore, as expected, the coordination between the rowers, as measured by the relative phase between the rowers' *CoM* movements, was indeed less accurate and less consistent in antiphase as compared to in-phase rowing. Yet, it was striking to see how little difficulty the rowers had to row antiphase, although they did it for the first time ever. This supports that also for crew rowing, next to in-phase, antiphase is an intrinsically stable state. Still, one of the nine pairs in De Brouwer et al.'s (2013) study showed a breakdown of antiphase coordination towards in-phase rowing, which led to the following examination.

Involuntary pattern switches

It is essential that the stability of the crew coordination, whether in- or antiphase, remains sufficient to maintain at high stroke rates, because 2000 m races are typically rowed at strokes rates above 30. Based on predictions of the HKB-model, one would expect the difference in stability between in- and antiphase crew coordination to increase with movement frequency. In fact, when gradually increasing the movement tempo, one might expect spontaneous switches from the less stable antiphase to the more stable in-phase pattern (Haken et al., 1985; Kelso, 1984) as was also shown in visually coupled humans (Schmidt, Carello, & Turvey, 1990).

In a recent off-water experiment (Cuijpers et al., 2015), we tested whether rowing in antiphase coordination would have the tendency to break down into in-phase coordination when increasing the tempo. To this end, eleven experienced male rowing pairs rowed in-phase and antiphase on the two-ergometer system on slides in a steady state trial (2 min, 30 strokes/min) and a ramp trial in which the stroke rate was increased every 20 s from 30 strokes/min to as fast as possible in 2 strokes/min steps. There was sufficient recuperation time between the four trials. Kinematics of rowers, handles and ergometers were captured (Vicon®, 200 Hz). Relative phase between rowers' trunk movements and between handles was determined. Continuous relative phase angle (CRP) was based on a procedure that took into account that the recovery phases lasted longer than the propulsive phases (see also Varlet et al., 2013). Moreover, in a rowing stroke more time is spent around the finish than around the catch of the stroke. Therefore, we also determined a discrete measure of relative phase (DRP) that is not sensitive to such small though impactful deviations from perfect harmonicity (see also De Brouwer et al., 2013), based on the moments of the catch (Kelso, 1995).

First of all, for most pairs the highest achieved stroke rate was higher for in-phase, which was ascribed to the reduction of ergometer movement in antiphase, knowing that on dynamic ergometers higher stroke rates can be achieved than on static ergometers (Colloud, Bahuaud, Doriot, Champely, & Cheze, 2006). Furthermore, two of the eleven pairs showed a breakdown of antiphase into in-phase crew coordination. Notably, these breakdowns occurred in the very beginning of the ramp trial (around 32 strokes/min). After the transition occurred, one pair tried to restore the antiphase crew coordination but did not succeed (see Figure 1). The other pair already showed difficulties maintaining antiphase coordination during the steady state trial (30 strokes/min); they indicated that they did not feel comfortable rowing in antiphase. Because transitions occurred at the initial tempo of the ramp trial and were also apparent in steady state trials (see also De Brouwer et al., 2013) we suspect that at these tempos the coordination of these two dyads might already have been too sensitive to perturbations (designating low stability), potentially related to (temporary) loss of concentration or attention (e.g., Temprado & Laurent, 2004).

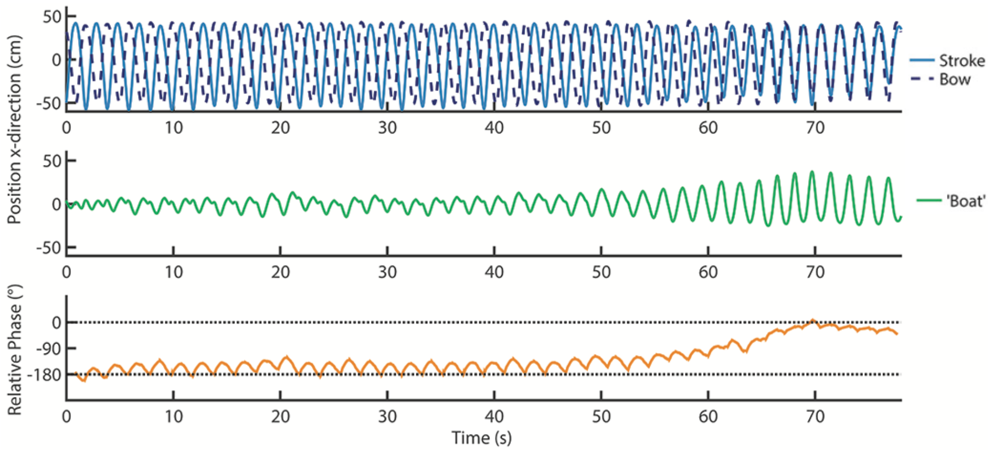

Figure 1. Transition from anti- to in-phase crew coordination at 32 strokes/min; movements of rowers (upper panel) and 'boat' (middle panel), and relative phase between the rowers (lower panel).

In any case, when antiphase rowing coordination is lost, it is difficult to return. This is also due to the mechanical coupling, because once the boat starts oscillating (see Figure 1) it is difficult to counter it. Regarding mechanical coupling, Christiaan Huygens already observed in the 17th century that two pendulums clocks on a wall that were initially uncoordinated, became coordinated over time in either an in-phase or antiphase pattern, because the clocks interact through the vibration in the wall. This was also demonstrated with mechanical metronomes that were jointly placed on a moving base (Bennet, Schatz, Rockwood, & Wiesenfeld, 2002; Pantaleone, 2002). In this non-living system, due to mechanical coupling via the moving base, the metronome pendulums are also attracted to in-phase synchronization when starting in antiphase[5]. Hence, in interpersonal coordination, a direct mechanical link forms a strong base for attraction to in-phase that is arguably more stringent than for perceptual coupling (Lagarde, 2013). In cases where two humans are mechanically coupled, it might require more 'mental effort' to stay coordinated in antiphase (see also previous paragraph), to prevent any attraction to in-phase from happening. For more discussion on this issue, see '*Sources of coupling*'.

Movement frequency

A second issue Cuijpers et al. (2015*)* could address was the predicted coordinative inconsistencies at increasing movement rate. Indeed, many interlimb coordination studies have confirmed that coordination deteriorates with movement tempo, and that for antiphase this effect is stronger than for in-phase (see Kelso, 1995). In rowing, stroke rates vary from 18-24 strokes/min during (endurance) training to 30 strokes/min for freshmen crews during racing, with Olympic crews often reaching up to 42 strokes/min (i.e., 0.7 Hz). It is therefore essential to know if the stability of the coordination pattern, whether in- or antiphase, remains sufficient at increasing stroke rates. The nine pairs that did not show a transition in the antiphase ramp trial were analysed in terms of the variability of DRP ('circular' standard deviation) and accuracy of CRP ('circular' absolute error) over steady state bins of each performed movement frequency.

Although the coordination was expected to deteriorate with increasing tempo, the results revealed no statistically significant effects of stroke rate on crew coordination (Cuijpers et al., 2015; Chapter 4). On the other hand, as mentioned at paragraph '*Crew rowing*', from on-water rowing studies there are some indications that crew synchronization might *improve* rather than deteriorate with increasing stroke rate (Hill, 2002). In fact, interpersonal pendulum swinging experiments demonstrated that at movement rates above 1.2 Hz (i.e., 72 cycles/min) coordinative variability increased with tempo, while for movement rates below 1 Hz (i.e., 60 cycles/min) coordinative variability *de*creased with tempo (Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998). The authors related the latter effect to the difficulty of moving at a rate lower than the preferred (or: 'natural') movement rate (see also next paragraph). Importantly, as the ramp trials

[5] Many movies are available on-line in which synchronizing metronomes are demonstrated, of which arguably the most illustrative can be found here: https://www.youtube.com/watch?v=yysnkY4WHyM and here: https://www.youtube.com/watch?v=5v5eBf2KwF8.

in Cuijpers et al.'s (2015; Chapter 4*)* study were designed to invoke phase transitions, they already started at a reasonably high stroke rate, namely 30 strokes/min. It is conceivable that at rates lower than 30 stroke/min a movement frequency effect emerges and becomes better visible. In this respect, recent on-water measurements suggest that in-phase crew coordination indeed deteriorates for stroke rates below 26 strokes/min (Cuijpers, et al., 2017).

Detuning: Within-crew individual differences

Differences between the oscillatory characteristics of the two components also affect the coordination (e.g., De Poel, Peper, & Beek, 2009; Schmidt & Richardson, 2008), generally modeled as a detuning parameter (i.e., $\Delta\omega$; Kelso, DelColle, & Schöner, 1990). Implemented in the HKB model, the detuning parameter induces specific lead-lag relations and a decrease of coordinative stability (Kelso et al., 1990). It has commonly been inferred to reflect a difference between the eigenfrequencies (cf. 'intrinsically preferred movement rate') of the two oscillators (e.g., Schmidt & Richardson, 2008). As we consider rowers in terms of limit cycle oscillators, we may expect their movements to possess a characteristic amplitude (e.g., reflecting stroke length) and eigenfrequency (e.g., reflecting individually preferred stroke rate). For instance, in an ergometer rowing experiment, Sparrow, Hughes, Russell, and Le Rossignol (1999) indicated that rowing at preferred rate was metabolically more efficient. When increasing or decreasing stroke rate while maintaining the same power output, the rowers for instance changed their stroke lengths (i.e. excursion of the handle), which lead to an increase in metabolic cost for both lower and higher rates. These results advocate that, for a given output level, each rower has its own individual 'optimal' stroke frequency and, hence, the eigenfrequency varies over individuals. Hence, if rowers with different eigenfrequencies and/or stroke amplitudes (cf. De Poel et al., 2009) are combined into a crew, not only the individual efficiency (see above) within the crew but, given the predictions from the HKB-model with detuning parameter, also the crew coordination may be compromised. As such, coupled oscillator dynamics provides an account for why it is beneficial to select rowers close to the same preferred movement frequency (and also in terms of other properties) into a crew.

Sources of coupling

In this paragraph, we briefly reflect on the merits that the task of crew coordination might have for examining (interpersonal) coordination dynamics in general, through delineating some issues regarding the sources that mediate interaction between rowers of a crew. The interaction, or coupling, may in general terms be considered as an information array between two rhythmically moving components. The majority of research on interpersonal coordination dynamics is done on movement synchronization mediated trough visual coupling (e.g., Oullier, De Guzman, Jantzen, Lagarde, & Kelso 2008; Peper, Stins, & De Poel, 2013; Schmidt et al., 2011). Evident in rowing, though, is the direct mechanical coupling through the boat. This physical link also allows for perception of haptic information about the others' movements through the movements of the boat that they share. Hitherto, mechanical and haptic coupling have received very limited attention in interpersonal coordination studies. Yet, many relevant examples used in such studies are highly dependent on such coupling, like dancing the tango or, indeed, crew rowing. Laboratory experiments showed that when dyads need to coordinate their actions on the basis of haptic information, they amplify their forces to generate a haptic information channel (Reed, Peshkin, Hartmann, Grabowecky, Patton, & Vishton 2006; Van der Wel, Knoblich, & Sebanz, 2011). This principle seems to hold for crew rowing as well, as Hill (2002) suggested that an increase in force output provides a better kinaesthetic perception facilitating the adaption of force patterns.

In rowing, the movements of each rower set the boat in motion, thereby moving the other crew members (similar to the coupled metronomes; Pantaleone, 2002). As such, mechanical interpersonal coupling may be considered as a source of perturbation requiring anticipatory movements (Bosga, Meulenbroek, & Cuijpers, 2010) but can also be seen as a source of support that stabilizes coordination patterns by mutually constraining the movements of the mechanically coupled agents (Harrison & Richardson, 2009). Most importantly, mechanical coupling differs from perceptual coupling (visual, auditory and haptic/kinaesthetic coupling) in that it is impossible to escape from: the body of each agent gets passively shaken by the movement of the other agent (Lagarde, 2013), whereas perceptual coupling is mediated by the degree to which an agent is sensitive to, or able to detect the pertinent information, for instance by means of attention devoted to the information source (Meerhoff & De Poel, 2014; Richardson et al., 2007). This implies that the mechanical coupling is more stringent than perceptual coupling.

Application to on-water rowing

The theoretical analysis of crew rowing from a coordination dynamics perspective already offered some nice new insights that can be rather directly applied to rowing practice. However, the lab is obviously not exactly the same as the real situation. For instance, in the lab studies of De Brouwer et al. (2013) and Cuijpers et al. (2015) there were no lateral and vertical (angular) movements of the 'boat', handles were used rather than oars (with a certain length and weight), oar handling technique and blade hydrodynamics were not present, etcetera. Therefore, testing on water is a next important step. Commercial measurement systems are available for analysing movements and forces in on-water crew rowing (e.g., Sève et al., 2013) and in recent on-water experiments with an Arduino-based measurement system (Cuijpers et al., 2017) we tested the hypothetical relation between the quality of crew coordination and unwanted, drag-increasing boat movements (as posed by Baudouin & Hawkins, 2002; Hill et al., 2009).

The case of antiphase rowing also offers quite a straightforward direct application to on-water rowing. Before it can be considered to implement in competitive practice, though, many research steps still have to be taken. This primarily involves biomechanical aspects that may cancel out the 5% velocity efficiency benefit, such as blade resistance and air friction, that remain to be further explored. Nevertheless, as delineated above, coordination dynamical examinations already showed that performing the antiphase pattern sec is not a problem at all, also not at stroke rates as high as in a rowing race. This was also confirmed in recent exploratory on-water try-outs by ourselves, using two experienced rowers. With some extra space between the rowers (because otherwise the blades would clash and/or the bow rower would hit the stroke rower in the back), on-water antiphase rowing appears to be quite easy to perform, even without any practice. Whether it indeed leads to higher average velocity is not clear yet; as noted, this requires testing with measurement equipment and further biomechanical evaluation of the problem. However, that was not within the scope of this chapter.

Concluding remarks

In this chapter, we illustrated the relevance of coordination dynamics for investigating crew rowing. Alongside issues such as the (differential) stability of coordinative patterns, (preferred) movement frequency and coupling in crew rowing, we showed how coordination dynamical research is particularly relevant in this context, how it may be applied to crew rowing, and also how the knowledge gained may be used for the benefit of improving performance. Together, this also further underscored crew rowing as archetype of interpersonal coordination dynamics, and the research reviewed in this chapter provides means for the example of crew rowing to now surpass the stage of mere metaphor.

Note that the manuscript included in this chapter slightly differs from the article that was originally published in Scandinavian Journal of Science and Medicine in Sports (2017), 27(12), 1697-1704. DOI: 10.1111/sms.12800. Specifically, due to issues in the calculation of the standard deviation of the continuous relative phase, this chapter only reports results regarding the standard deviation of the discrete relative phase (around catch and finish). Accordingly, the relations between crew coordination consistency and movements of the boat are based on the discrete relative phase around catch and finish. Note that this adaptation had no qualitative consequences regarding the original interpretations in the published article.