Ecological dynamics of continuous and categorical decision-making: The regatta start in sailing

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Ecological dynamics of continuous and categorical decision-making: The regatta start in sailing

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Abstract
Ecological dynamics of decision-making in the sport of sailing exemplifies emergent, conditionally coupled, co-adaptive behaviours. In this study, observation of the coupling dynamics of paired boats during competitive sailing showed that decision-making can be modelled as a self-sustained, co-adapting system of informationally coupled oscillators (boats). By tracing the spatial–temporal displacements of the boats, time series analyses (autocorrelations, periodograms and running correlations) revealed that trajectories of match racing boats are coupled more than 88% of the time during a pre-start race, via continuous, competing co-adaptations between boats. Results showed that both the continuously selected trajectories of the sailors (12 years of age) and their categorical starting point locations were examples of emergent decisions. In this dynamical conception of decision-making behaviours, strategic positioning (categorical) and continuous displacement of a boat over the course in match-race sailing emerged as a function of interacting task, personal and environmental constraints. Results suggest how key interacting constraints could be manipulated in practice to enhance sailors’ perceptual attunement to them in competition.

Keywords: Co-adaptation, cognition, dynamical systems, emergence, decision-making, tactics, time series analyse

Match-race sailing can be described as a duel between two boats in which environmental constraints such as wind strength and direction, ocean currents as well as relative positioning of opponents have to be considered in order to achieve the performance goal of crossing the finish line first. One aspect of performance that requires careful analysis is how potential race-winning decisions are made during competitive performance in order to position the boat carefully to exploit wind and ocean currents in achieving the main task goal (see Allen & De Jong, 2006 for a review).

In the crucial pre-start period, there is no single “valid” course for each boat to follow, so the boats engage in an intensive pre-start competition, in which each continuously tries to gain a positional advantage over the other. With evenly matched boats, a good start usually results in a match-winning performance (Saltonstall, 1996), mainly because the first boat to cross the start line can gain a distinct advantage by “covering” the other boat, i.e., attaining strategic placement to block its wind. However, with effective handling and strategic use of wind and currents, a trailing boat can escape the grasp of the leader, pass and maintain dominance right up to the finish line. Analysis of sailors’ control of boats during the pre-start period reveals that, although decisions regarding the discrete optimal starting place could be made in advance, this tactic is inherently misleading because of the need to consider and interact with instantaneously changing task and environmental constraints (Araújo, Davids, & Serpa, 2005; Pluijms, Cañal-Bruland, Kats, & Savelsbergh, 2013). These constraints include: (1) wind direction in the upwind phase and its relation with the starting line; (2) movements of opposition boats in trying to keep or gain positional advantage (control) over the other boat; and (3) the ebb and...
flow of ocean currents. There is a need to understand the nature of the behaviours that emerge to seek information in adjusting the sailors’ underlying performance strategy. This is because each sailor’s decisions are embedded in actions towards achieving task performance goals (Araújo, Davids, & Hristovski, 2006; Araújo, Rocha, & Davids, 2011).

From this characterisation of decision-making behaviours in the pre-start period and during match-race sailing events, questions are raised over the usefulness of normative models of decision-making in sport psychology. The task constraints of typical cognitive decision-making studies are much narrower, supported by the rational, normative approach to decision-making, in which option selection is based on a mental model of performance contexts built up with experience (see Bar-Eli, Plessner, & Raab, 2011 for a review). Normative approaches have been shaped by economic models and propose that decisions are made according to a value-maximising principle, implying a rational and conscious process of selecting options that will maximise the utility for the performer in explicit cost–benefits analyses undertaken (Hastie, 2001). In such traditional models of decision-making, if putatively “optimal” performance solutions (normatively defined) are not achieved, it is assumed that performers have not been “rational” enough, a form of circular logic (Goldstein & Gigerenzer, 2002). From this normative perspective, the process of making optimal decisions in sailing is dependent on a comparison of key constraints including wind direction, adversary position and distance to line with a putative internalised model of how to optimally respond during performance, given these constraints. Importantly, normative models of decision-making are designed to account for the selection of one action at one point in time. The incorporation of future events in these models occurs by assuming that the decision-maker anticipates some possible consequences by constructing imaginary scenarios as propositional extensions of his/her mental situation model (Körding & Wolpert, 2006).

Here we show that ecological dynamics models of decision-making (Araújo et al., 2006) imply that sailors’ decisions can be viewed as emergent co-adaptive behaviours of sailors and the performance environment and may be highly functional for achieving competitive goals, even when failing to start the race at what may be normatively considered as “the” optimal point on the start line, i.e., making a categorical selection. To understand this different view, it is necessary to take into account the interactive effects between environmental and individual constraints that influence emergent decision-making behaviours in a sailing regatta (Araújo et al., 2006; Pluijms et al., 2013). The theory of ecological dynamics proposes that decisions emerge at the individual–environmental level. This important idea signifies that not only is the mind of the performer instrumental in decision-making, but also the constraints of the local environment play a large role in regulating behaviour (Richardson, Shockley, Fajen, Riley, & Turvey, 2008). The implication is that decision-making in sport should be considered as a temporally extended process that is constrained by the intertwined relations between intention, perception and action in a continuous way (Araújo et al., 2006). In performance environments such as a sailing regatta, a course of action evolves in real time (i.e., it is not discrete) and this type of intentional behaviour needs to be rationalised by models of decision-making (Shaw, 2003).

In ecological dynamics, time-extended analyses of pre-start periods in match-race sailing have revealed unexpected structure in actions observed (Araújo et al., 2006). This is because sequences of linked decisions in a dynamic task reveal conditional coupling, a property of complex, dynamical systems in nature (Van Geert, 1994). Each separate decision in activities like sailing should not be viewed as functionally independent (i.e., categorically separate) from other decisions emerging from the performer during performance. Behaviour that is conditionally coupled occurs because the state of a dynamical system (i.e., a match-race regatta) at any one moment remains dependent on previous states of the system. For example, interactions with an adversary during the pre-start period clearly constrain the choice of start line locations for each competing sailor. Understanding momentary accuracy of snapshot decisions (e.g., a decision to approach or avoid the adversary in each local interaction) may be less important than understanding a performer’s accumulated accuracy of decision-making behaviours emerging from continuous interactions within the performance context geared towards achieving an overarching goal (e.g., acquire an advantageous position in the starting line when a regatta commences; Araújo, Diniz, Passos, & Davids, 2014; Araújo et al., 2005).

Analyses of performance during match-race sailing can provide revealing insights in the theory of ecological dynamics. In our study, investigating the emergence of continuous decision-making behaviours over time which regulate competitive sailing performance, we expected to observe how the leading boat would seek to control the other boat in the competition. Consequently, the trailing boat would need to achieve performance goals (e.g., to start at the most favourable start line position protected by the other sailor) by choosing a different trajectory to that adopted by the leading boat, creating an emergent self-sustaining oscillatory behaviour (Gopalsamy, 1982). This process was expected to lead to the emergence of...
continuous interactions in the dyadic context of match-race sailing performance since there is not enough information present to select beforehand a path to an optimal discrete start point. Consequently, the selection of a goal path by each boat can be modelled as an emergent self-organised process. The continuous creation, maintenance and dissolution of these states of coupling between the co-adapting boats are predicated on information about the coordinative state of the system formed by participants/boats, the local performance constraints and their dynamics. Research has revealed that interpersonal coordination patterns arise from co-adaptive self-organising processes in natural systems, even when coordination may be an unintended consequence of other interaction goals (see Schmidt & O’Brien, 1997).

A second expectation concerning categorical (i.e., discrete) decision-making is that, by manipulating the discrete optimal location for starting, we expected to be able to identify, in successive regattas, evidence of phase transitions in the decision “where to start”. We considered that phase transitions in decision-making would emerge from manipulation of key information sources for competitive sailors, demonstrated as the angle between the wind direction and the line (in line with previous data reported by Araújo et al., 2006). One would expect to observe sudden jumps in categorical decisions in successive match-races starts, because sailors would seek to align local continuous decisions, emerging from their active exploration of situational constraints (e.g., the continuous interactions with the other boat in a competitive environment), with distal decisions about optimal start locations.

## Methods

Fifteen sailors, 13 male and 2 female, aged 12.1 years ($s = 1.6$) with 3.3 years ($s = 0.7$) of experience participated in the study, each using an “Optimist” type boat.

Several type-80 Silva compasses were used to take azimuth measurements to define the location of a boat on the starting line relative to the wind direction and its positioning at the first mark and also to measure wind direction variations during starting procedures. Wind strength was measured with an anemometer (Turbo Meter, Davis instruments, Hayward, California). These measurements were synchronised and registered every 5 seconds, from the beginning of a 2-minute, pre-start period until the race start (“second zero”). The ethics committee of the Faculty of Human Kinetics granted ethical approval for the study.

Two digital cameras were used to collect data on positioning and location of racing yachts, with one camera placed on land, behind the starting line being used to register boat displacement (Canon XL1, Mini-DV). The other camera (Sony DCR TRV310E PAL D8) was placed on the mark’s yacht and used to accurately define the location at which a boat crossed the starting line. To avoid inordinate effects of unstable environmental constraints on decision-making, like wind shifts or changes in ocean tides, Cascais Bay, near Lisbon in Portugal, was chosen as the testing site because of the stability of its winds, and because the tide tends to remain constant and light.

In pairs, matched according to rank proximity, sailors performed in two successive regattas (30 in total), following official regatta rules, except that the pre-start period lasted for 2 minutes (instead of five). The regattas were scaled to the experimental area, being shorter than typical, with the first mark 50 metres after the starting line. This short distance was used so that the selected starting point could wield a significant influence on regatta performance in this scaled experimental context. Sailors were instructed to complete the regatta as quickly as possible to ensure that the start was not disembedded from the competitive match race. The distance between the Committee Race yacht and the mark’s yacht (the imaginary starting line) was about 30-metres long. After the start, each regatta lasted for about 10 minutes.

Also, for each regatta, we manipulated the angle between the wind direction and the starting line in successive positions, $10^\circ$ apart, to observe whether there were discontinuities in the decision “where to start”. These manipulations were performed by the investigators 5 minutes before the regatta started. Due to subtle wind shifts, these angles could be modified. Therefore, we assumed that the optimal starting location was the one observed in participants’ actions at “second zero”. Only the regattas in which the sailors started from the start location, where the wind angle was favourable, were considered in this particular analysis ($N = 13$). For this part of the study, we wanted to demonstrate the existence of a phase transition in a categorical decision in each race.

We quantified the number of times the boats started at the optimal point by dividing the start line into three equal parts: from $-60^\circ$ to $-10^\circ$ we considered this section as favouring the committee race (left-hand side); from $-10^\circ$ to $10^\circ$, we considered this to be the neutral section (middle); and from $10^\circ$ to $60^\circ$, we considered this section as favouring the mark’s yacht (right-hand side).

Based on this three-section division of the start line, immediately after the regatta, we used a retrospective verbal protocol (Ericsson & Simon, 1993, see also Araújo et al., 2005), asking each sailor for three judgments: (1) “Where was the optimal starting
place in this race?”; (2) “Where did you actually start?”; and (3) “Where did you want to start?”.

Kinematics of the displacement of each boat were obtained by real-time tracking from a semi-automatic registration system, TACTO, developed in our laboratory (Fernandes, Folgado, Duarte, & Malta, 2010). Kinematic data for each yacht were later synchronised to time of onset of data collection, as determined from the instant that the jury flag signalled the 2 minutes for starting procedures. In each frame one point on each boat was digitised: the base of the yacht’s mast. Data from the Race Committee’s yacht, the mark’s yacht and the first mark were constantly collected in order to recalibrate the reference points, frame-by-frame. The x–y coordinates, sampled at 5 Hz, were then used to determine the distance of the boat to the optimal point in the starting line. This sampling value was based on the previous work (i.e., Howarth, Walsh, Abernethy, & Snyder, 1984) who found that the time needed to make a perceptual judgement of an event finished 200 ms before the beginning of the first anticipative movement of the athlete. It has to be noted that those estimates emerged from a study of rapid actions in baseball. In sailing, the movement of the boat is obviously much slower, therefore not demanding such fast perceptual judgements. For example, an extremely fast sailing boat may travel at 40 knots (74 km/h, see Anderson, 2008). However, baseball pitchers may throw fastballs at speeds of 105 mph (168.98 km/h, see Repanich, 2010).

The distance from the boat to the most favourable point relative to the wind direction was measured in metres. This point was obtained at the exact moment of the start, i.e., at the “second zero” of the pre-start race. Distance data were collected every 200 ms, during the pre-start period in every trial (with a maximal duration of 120 seconds). Distance data from the boat to the optimal start point, relative to wind direction, were then filtered at 6 Hz with a low-pass, zero-phase filter. We considered the leading boat to be the one nearest the optimal start point.

Time series were analysed in the time and frequency domains with autocorrelation functions and normalised periodograms, respectively (Brockwell & Davis, 1991; Fonseca, Diniz, & Araújo, 2014). The continuous coupling between the pairs of boats was statistically evaluated with running correlations (Derrick & Thomas, 2004; Duarte et al., 2012).

Results

Path selection to the optimal starting point: continuous decision-making

The time series referent to the distance, in metres, from each boat to the optimal starting position presented a roughly cyclical pattern. Here, we present two extreme exemplars of more correlated and less correlated (in absolute value) pairs of boats from our sample (Figure 1). These series have length (n = 579) corresponding to a duration of 115.60 s, according to the length of the shortest time series.

The cyclical pattern is illustrated by the time series relative to the distance from the sailing boat 16 to the optimal starting position. The sample autocorrelation function $\hat{\rho}(\cdot)$ at lags $k = 0, \ldots, 350$ with the critical bounds $\pm 1.960/\sqrt{579} = \pm 0.081$ of this time series is presented in Figure 3 (top). The corresponding normalised periodogram $\hat{I}(\cdot)$ at frequencies $\lambda_k = 2\pi r$ with $r = 0, \ldots, 0.5$ is shown in Figure 2 (bottom).

The sample autocorrelation function estimates the strength of the statistical dependence of the process at each time lag. It can be observed in Figure 2 (top) that the sample autocorrelations exhibit a cyclic pattern lying outside the critical bounds, with the sample autocorrelations being significant and taking positive values at certain lag values, as well as negative values at other lags.

From the normalised periodogram, it is possible to identify the dominant frequencies in the time series that are associated with hidden periodicities. It can be observed in Figure 2 (bottom) that the periodogram ordinates exhibit a high peak at a given frequency. The peak is significant and occurs at the specific frequency 0.00518 which implies a period of $1/0.00518 = 193$. This finding signifies that the series indeed display a cyclic pattern, repeating itself roughly every 193 time units, i.e., every 38.60 seconds. A relaxation time at 38.60 seconds of only

![Figure 1](image1.png)

![Figure 2](image2.png)

Figure 1. Two exemplars of time series referent to the distance, in metres, from pairs of boats to the optimal starting position with higher correlation (top) and lower correlation (bottom), relative to boats 1 and 2 and boats 15 and 16, respectively.
one boat illustrates the cyclic approaching and avoidances to and from the optimal starting point. This cyclic behaviour could not be captured, without being self-sustained through co-adaptation with another competitor. Each race presented a unique cyclic pattern.

Running correlations with a 10-point window (Duarte et al., 2012) were used to analyse the informational coupling between time series of the two competing boats, which underlay their co-adaptations, during the pre-start period, for all the races. On average, displacement of the two boats involved in all regattas was coordinated (in absolute values $|r| \geq 0.7$) 93.91% of the time ($s = 1.90; N = 15$). This observation indicates that the cyclic pattern of each time series was an emergent feature of two boats coupled by perceptual information engaged in a competitive regatta. Transitions from positive to negative correlations between the two boats exhibited the cyclical pattern, previously presented. Figure 3 presents the running correlations of the time series displayed in Figure 1, with higher values (top, correlated at $|r|$ ≥ 0.7, 96.81% of the time) and lower values (bottom, correlated at $|r|$ ≥ 0.7, 88.42% of the time).

By subtracting the distance from one boat to the other, relative to the optimal point over time, we were able to calculate zero crossings (Elliott, Chua, Pollock, & Lyons, 1995) to indicate the number of times that there was a change in the leading boat in each regatta start. These calculations provided a measure of co-adaptive behaviours during the race. We found that, on average, there were 2.87 crossings per race ($s = 1.60; N = 15$, Max = 6; Min = 0). Importantly, of the 30 occasions that a boat started the race, optimal positioning occurred on 13 occasions (43.3%).

Selection of the optimal start location: categorical decision-making

We observed that the boats’ positions tended to be at the extremities of the start line with higher $|\text{angle}|$ values (>10°) (Figure 4). In fact, when the wind favoured one of the extremities of the starting line, the nearer to that extremity the boat was positioned, the more direct was the required trajectory (to the first mark of a regatta). Interestingly, the start position near the committee boat tended to be undervalued because of the starboard priority (Figure 4).

![Figure 2](image1.png)

Figure 2. Top graph: sample autocorrelation function of exemplar data of the distance from the sailing boat 16 to the optimal starting position, at lags $k = 0, \ldots, 350$ with critical bounds (dashed lines). Bottom graph: normalised periodogram of the same time series, at frequencies $\lambda = 2\pi r$ with $r = 0, \ldots, 0.5$.

![Figure 3](image2.png)

Figure 3. Running correlations with higher (top) and lower (bottom) absolute values in pre-start races, relative to boats 1 and 2 and boats 15 and 16, respectively.

![Figure 4](image3.png)

Figure 4. Mean starting positions of the match-race boats on the "second zero", according to the wind/line angle.
However, in the zone where the wind was neutral (between about $-10^\circ$ and $+10^\circ$), there was higher variability in start location, because there was no advantage from boat positioning for the required trajectory. We also observed that phase transitions occurred in the same region (between about $-10^\circ$ and $+10^\circ$).

Finally, results of the verbal protocols showed that sailors accurately judged 52% of the 30 starts from the optimal section of the start line and in 66% of trials sailors knew where they had started. In 47% of trials the start point coincided with the participants’ intended position.

**Discussion**

Results showed that an informational coupling existed between the boats during the pre-start positioning sequence. This finding indicated that the path towards the perceived optimal point on the start line was assembled during the pre-race interaction between the boats and not established in advance by participants. Furthermore, since both boats in a race wanted to achieve an optimal start, their interactions created a self-sustained competitive system in which co-adaptations between members were sensitive to environmental, task and individual influences (Gopalsamy, 1982), thus explaining emergence of decision-making behaviours. Importantly, decisions clearly emerged under interacting constraints, and were not determined by one single source of constraint, such as a mental representation of a start in a competitor. We observed that, in match-race sailing performance, co-adaptive competitive behaviours between boats (the cycles and their oscillations) exemplified interpersonal self-sustaining, and thus self-organising, processes occurring during continuous decision-making behaviours. This process of decision-making (the selection of a path to the optimal starting point) clearly cannot be based on mental comparisons between optimal and actual states represented internally, because they emerge under the interaction of constraints such as an adversary’s actions, wind changes, ocean currents and personal preferences. Due to the high computation load required, it would be highly infeasible to be able to precisely calculate the exact state of each source of constraint such as the adversary, wind, tide and own personal/boat movements, then predict their changes, and plan how to act accordingly, on a moment-to-moment basis. Moreover, an ecological dynamics explanation of decision-making demonstrates biological plausibility, since it has already been observed in other organisms (Visscher & Camazine, 1999). It also demonstrates evolutionary plausibility, since individual differences in decision-making are a function of adaptive and random variations (Kenrick, Li, & Butner, 2003). Finally, it demonstrates neurophysiological plausibility, since decisions and action initiation cannot be predicted in advance (Schall, 2001). Furthermore, it does not require the speculative need for a central executive controller located in each sailor’s central nervous system (CNS) (Richardson et al., 2008).

Results demonstrated the existence of phase transition phenomena in the decision “where to start”, according to our manipulations of the angle between the wind direction and the line. Interestingly, the optimal point preferred by sailors was not the same as for the experimenters, as the results showed. Since the one selected by experimenters was validated by coaches and defined in advance, it is clear that the functional point for starting a match race does not need to be a normative optimal point, proposed by normative models. The adaptive behaviours of sailors revealed situated solutions emerging from the momentary interactions of key task and environmental constraints.

It seems that sailors manage the load of particular indices of information (e.g., wind, adversary, their own manoeuvres and internal states) needed to regulate their actions by becoming perceptually attuned to specific higher-order information of the performance environment – aspects that gain special significance because of the specificity of the task constraints (Shaw, 2003). This finding was clearly shown by the sailors’ difficulties in making accurate judgements about their own behaviours, revealing that the issues that they could verbalised did not capture the most significant information they used when sailing. It seems that practice attunes performers to the perceptual variables that reliably specify states of affairs relevant to a specific task (Araújo et al., 2011). In this way, athletes can use the situation as its own best model (Brooks, 1991) and actively explore it, sampling it in detail at specific locations according to the particular needs of the moment. Decision-making in sport environments may be best understood in terms of the interactions of multiple local constraints (location of the yachts and of the starting line, their speed, sailors’ cognitions, age and morphology, the currents, wind directions, etc.). Performers’ situated cognitions are a fundamental means of using active strategies that leave much of the information out in the natural world, and carefully using real-time sequences of body-context interactions to solve problems in a robust and flexible way. The model of decision-making promoted here involves coupled complex systems, at the person-environment scale of analysis (e.g., a sailor and the regatta context), whose joint activity leads to emergent solutions.

Blakemore and Robbins (2012) showed that decision-making in adolescents, like the sailors in
this study, is particularly sensitive to social contexts, since it occurs in a competition with peers. In their study, they were focusing on the role of the brain in decision-making, and therefore the influences of the multiple constraints that explain decision-making behaviours were not considered. Nevertheless, the sensitivity of adolescents in social contexts may indicate that samples at this age are particularly relevant to understand how competitive expertise develops in sport. However, the degree of generalisability to adult performance is limited in the present study and is an issue for further research.

In sum, there are several constraints that channel decisional behaviours in the start procedures of regatta sailing. Therefore, it is important that sailors learn to act according to contextual demands rather than merely acting from memorised behaviours, and ignoring relevant informational variables. We observed that sailors may not perceive changes at the most favourable side of the starting line, particularly during the final 38 seconds. This may have been due to weaknesses in their position during these moments that may not have allowed them to detect the relevant wind-starting line angle (cf. Oudejans et al., 2000). Another possibility that may have consequences for training is that these sailors had some difficulties in starting near the pin-end boat, even when this was the most favourable place to start (Araújo et al., 2006). The sailing coach may train the decision-making of developing sailors relative to these tactical issues by manipulating key constraints such as: (1) the angle of the starting line with the wind direction; (2) the regatta course, by changing the starboard mark to the left or to the right of wind direction; (3) the presence or the absence of adversaries (and the number of them) in certain parts of a training regatta; (4) the signals made by the coach during performance; (5) the number and place of marks in the regatta; and (6), the time to the start. Importantly interactions between these constraints during training should be encouraged. For example, with a shorter starting line, the influence of adversaries will be greater than when a longer line is used.

These findings suggest that continuous and categorical decision-making in sports like sailing is an emergent process that should be developed through the active exploration of situational constraints, such as competitor intentions, wind direction, water currents, manoeuvres and adversary positioning.

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