Coordination Dynamics of Upper Limbs in Swimming: Effects of Speed and Fluid Flow Manipulation

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Coordination dynamics of upper limbs in swimming: Effects of speed and fluid flow manipulation

Running head: Constraint impacts on crawl coordination dynamics

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Abstract

Purpose: Motor outputs are governed by dynamics organized around stable states and spontaneous transitions: we seek to investigate the swimmers' motor behavior flexibility as a function of speed and aquatic environment manipulations. **Method:** Eight elite male swimmers performed an eight-level incremental test (4% increment from 76 to 104% of their mean speed on 200 m front crawl) in a quasi-static aquatic environment (pool). Another incremental test at similar effort was then perfomed in a dynamic aquatic environment (swimming flume) up to maximal speed. Stroke rate (SR), index of coordination (IdC) and intersegmental coupling of the upper limbs were computed from the inertial sensors located on the upper limbs and the sacrum. **Results:** With speed increase, SR values presented a steeper linear increase in the pool than in the flume. IdC values increased also in the pool, but remained stable in the flume. Individual SR and IdC vs. speed increase displayed second-order polynomial dynamics, indicative of adaptive flexibility with a range of extremum values more restricted in the flume. Finally, a reduction of the in-phase coordination pattern was noted with flume speed increase. **Conclusions:** Action possibilities were strongly constrained in the flume at highest speeds as the fluid flow led to discontinuity in propulsive actions of the upper limbs and lack of in-phase inter-segmental coordination. This highlights that the behavioral flexibility was restricted in the flume in comparison to the pool, in which the exploitation of opportunities for action involved larger number of degrees of freedom in the movement.

Keywords: Motor flexibility; Constraints; Individual–Environment coupling; Motor control.

According to the ecological dynamics theoretical framework, complex neurobiological systems (e.g., human behavior) displayed *self-organization* properties between cells, muscles, bones, and limbs to act functionally in performance environments (Davids et al., 2013). Self-organization is a concept by which "temporal, spatial or spatial-temporal patterns evolve without being imposed on the system from the outside" (Haken, 1983; p.56). Moreover, the *emergence* of functional motor behaviors is continuously bounded by the interactions of three categories of constraints (Newell, 1986). *Environmental* constraints largely related to the environment in which the task is performed. All individual characteristics of a performer denoted *organismic* constraints while attributes relative to the specific goals of an activity are *task* constraints.

Manipulating these dynamic and interactive constraints can influence the set of ordered and functional movements, which may emerge when an individual is performing any behavior (Davids et al., 2003). In cyclical competitive sports, where the task goal is to cover a given distance in the minimum of time, the movement efficiency is directly linked to the minimizations of the fluctuations of the individual's center of mass movement speed (see Gourgoulis et al. 2018 for an example in swimming). Manipulating either the movement speed or its components (i.e., stroke frequency and stroke length) revealed that the locomotor system is governed by dynamics organized around stable states and spontaneous transitions. As an example, human locomotion on a treadmill was characterized by a walk-run transition while speed gradually increased over the range 0.9-3.6 m/s (Diedrich & Warren, 1995). In this study, the relationships between speed increase and gait pattern was not linear as the proportional speed increase led to a transition from walking to running, and was associated to energy expenditure minimization. This example illustrates that each gait pattern has a relative range of flexibility over which new gait pattern emerges.

Increasing the movement speed on land does not fundamentally increase the task complexity (or the energy requirement to perform the task), whereas this constraint can play a much more decisive role in other environments. For instance, since water is 800 times denser than air, every action is performed with very low propelling efficiency (0.5–2.2%) in comparison to movements performed on dry land (20–25%; [Toussaint, Hollander, van den Berg, & Vorontsov, 2000]). Additionally, aquatic motricity is generally not performed in a purely static environment but one that is quasi-static or clearly dynamic that can be problematic for producing and controlling movement. This was exemplified in swimming by Cohen, Cleary, and Mason, (2012) during a dolphin kick, with the use of smoothed particle hydrodynamics: kicks generate fluid structures travelling diagonally up or down away from the swimmer, but also rotational motion of the particles. It means the fluid may spontaneously change its state to a fully turbulent flow either due to an increase of its own velocity or as a function of swimmer’s movements. Therefore, the movements of water particles become incoherent, chaotic, or even unpredictable, notably visible at the surface (Kundu, Cohen, & Dowling, 2012). At the opposite, quasi-static aquatic environments (or environments flowing at very slow speeds) present water particles flowing in parallel streamlines, defined as laminar flow. Moving through the fluid or manipulating the flow speed directly influences the resistances that an individual is facing, since resistance depends on the square of the speed of the fluid displacement (Zamparo, Gatta, Pendergast, & Capelli, 2009). Among all constraints surrounding a competitive swimmer, speed of movement and fluid resistance appear as one of the major biomechanical determinants performers have to face when they are moving through water.

Characterizing the effect of movement speed on coordination dynamics was extensively tested in front crawl (Chollet, Chalies, & Chatard, 2000; Komar et al., 2012; Seifert, Boulesteix, & Chollet, 2004a; Seifert, Chollet, & Bardy, 2004b; Seifert, Chollet, & Rouard, 2007), since swimming speed determines performance. Much of this work focused on the coordination between the upper limbs, by computing the Index of Coordination (IdC) (Chollet et al., 2000). The IdC assesses the time gap between two propulsive actions based on kinematic measurements. In those previous works, both the stability (i.e., the persistence of motor behaviors in response to external constraints) and flexibility (i.e., the range of individual motor repertoires in given performance situations) of expert behaviors at different swimming speeds were investigated. Those studies mainly focused on expert swimmers as behavioral adaptability (as a subtle blend between stability and flexibility, for more details, see Davids et al., 2013; Seifert, Button & Davids, 2013) reflect the skill of human to exploit the environmental and organismic resources to reach the task goal. As an example, those researches reported a spontaneous shift of the IdC values (Seifert et al., 2004a; Seifert et al., 2004b) from catch-up mode for middle distances towards opposition/superposition coordination for sprint speeds (superposition indicated an overlap of the propulsive actions of the two upper limbs; [Komar et al., 2012; Seifert et al., 2007]). Using a protocol to scan all possible swimmers' behaviors (e.g., by increasing linearly the swimming speed) may conduct to the spontaneous and non-prescribed emergence of a new coordination mode (Seifert et al., 2007). Due to the constraints that surround swimming motion, several profiles could be determined: some swimmers were able to face the constraints but remained not very flexible (i.e., reaching high swimming speeds by always using the same coordination), whereas others were highly flexible to reach the task goal (i.e., high swimming speeds with a wide repertoire of motor solutions: IdC variations) (Bideault et al., 2011). In this sense, the manipulation of these constraints would be of valuable interest to challenge the swimmers' behaviors, and more broadly to test for their range of motor repertoire (i.e., action capabilities).

The main aim of this study was therefore to scan the coordination dynamics of expert swimmers as a function of the increase in swimming speed coupled with a manipulation of their swimming environment (i.e., using a flume [Guignard et al., 2017] *vs.* using a swimming pool). Specifically, we used a scanning task to test the behavioral flexibility in order to understand whether swimmers were more likely to use a wide motor repertoire and/or a restricted number of stable states to achieve the task goal (Guignard et al., 2017). We hypothesized that the flume would narrow the landscape of affordances (Rietveld & Kiverstein, 2014) (i.e., action possibilities offered by the environment relative to the swimmer's capabilities) in comparison with swimming in a traditional pool, both in term of low-order behavioral variables (e.g., stroke rate [Hay, 2002]) and high-order behavioral variables (e.g., coordination). Indeed, the task goal achievement in the flume is conditioned by the creation of continuous propulsion to sustain the speed imposed by a turbulent and wavy fluid flow (e.g., it is hard to glide against the fluid flow in the flume [Guignard et al., 2017]). For these reasons, swimmers' behavioral adaptations would be mainly visible for coordination of the upper limbs (due to dynamic fluid flow) but also coordination within the different segments composing the upper limb (difficulty to position distal extremities).

Methods

Participants

Eight elite (national- to international-level specialists of the 200 m front crawl event, training more than ten times a week) male swimmers (mean ± SD age: 20.8 ± 2.96 years, height: 186.8 ± 3.4 cm, mass: 79.75 ± 7.81 kg) volunteered to participate in this study (they had no history of injuries and gave written consent). The protocol was approved by the local University ethics committee (ID: ED556HSRT) and conducted in accordance with the ethical standards of the Declaration of Helsinki. Swimmers' level was expressed as a percentage of the current world record (WR) for the 200 m freestyle: the participants' mean ± SD best times represented 90.61 ± 1.65% of the WR.

Set-up

The first part of testing took place in a 50 m indoor swimming pool (in order to set the targeted speeds), before relocating to a specially designed swimming flume (Italian National Olympic Committee; 6.20 m long, 2.90 m wide and 1.30 m deep, with a water temperature around 27°C) for the second part of the experimentation. Flume functioning and calibration procedures are extensively explained in Guignard et al. (2017). In the eventuality swimmers were unable to sustain the speed imposed by the flume flowrate, a safety net was positioned aft. All swimmers were acquainted with swimming in this flume, as they had already used it for training or had been familiarized with the flume prior to the present tests.

Procedure

After a standard 10 min warm-up performed in the pool, swimmers performed 8×50 m bouts at 76, 80, 84, 88, 92, 96, 100 and 104% of their mean speed as obtained during their best race time on 200 m front crawl (corresponding to average absolute speeds of 1.33 [speed 1 or S1]; 1.41 [S2]; 1.45 [S3]; 1.53 [S4]; 1.58 [S5]; 1.65 [S6]; 1.69 [S7] and 1.77 m/s [S8]). Two experimenters imposed the target speeds, the first acting as a pacer (holding a pole) and the second controlling the speed at the end of the pool, as extensively described in Guignard et al. (2017). Without removing their testing equipment, swimmers were immediately transferred to the swimming flume to commence the same incremental protocol. We considered that maximal effort during a 200 m front crawl (where 70-90 cycles were performed in 1 minute 50 seconds to 2 minutes) could be compared to a maximal effort of 1 minute 50 seconds to 2 minutes in the flume. Based on the maximal swimming speed achieved during swimming 2 minutes at maximal intensity in the flume, relative speeds for eight bouts at submaximal intensity were computed following the same increments than previously selected in the swimming pool. Swimmers started the test between 76 to 80 % of the maximal speed they were able to sustain in the flume. Subsequent trials with 4% intensity increment were then performed, and the test ended when swimmers finished a trial in the net behind them. In these conditions, swimmers performed from 6 to 8 trials over forty cycles;

the first ten cycles corresponded to time necessary to obtain a stabilized water surface in this short channel flume model. Slowest swimming speed achieved in the flume was 0.96 m.s^{-1} while highest speed was 1.41 m.s^{-1}. Notably, the swimmers globally had to swim above a positional marker on the bottom of the flume. Both the pacer at the pool and the positional marker in the flume performed informative rather than restrictive functions (a tolerance of 0.5 m was authorized), and should not denaturalize the swimming motion. Moreover, no instruction was given regarding the breathing action, and all swimmers spontaneously inhaled on the right, left or on both body sides. For the present study, only the right side upper limb coordination was considered, independently of the breathing action (excepted for IdC computation, necessitating information from both body sides). Each swimmer was allowed one-minutes rest between each bout in the pool and in the swimming flume.

Data collection

The durations of stroke and stroke phases and the upper limb inter-segmental coordination were recorded using seven inertial measurement units (IMUs; Hikob, Villeurbanne, France) positioned on the dorsal side of the hand, the lower arm and upper arm of both body sides (to avoid significant kinematic imbalances between left and right), and at the sacral level. Each IMU (sampling frequency of 100 Hz) measured 45×36×17 mm and was composed of a three-dimensional (3D) accelerometer (± 16G), a 3D gyroscope (± 1200 °/s) and a 3D magnetometer. To be waterproofed, sensors were placed within plastic bags and then affixed to the skin with a therapeutic strap and adhesive tape (Guignard et al., 2017).

To obtain the sensor orientations in the 3D field, the magnetometers were held above the pool and the flume for calibration, in order to reduce magnetic distortion during data processing. Other calibrations (performed during rest periods) maintain alignment of sensor axes to the anatomical body axes, to obtain analyses that would be insensitive to the IMU orientations despite the multiple body configurations in the swimmers' sample. Such procedures consisted of sequences of upper limbs movements repeated five times: flexion-extension around the transversal axis and prono-supination around the longitudinal axis.

Data analysis

The data were processed using Matlab r2014a (The MathWorks, Inc. Natick, MA, USA). To obtain angles from raw data recorded with the IMUs, we used the complementary filter of Madgwick, Harrison, & Vaidyanathan (2011) in the manner of Guignard et al. (2017). Segmental angles, or angles between the 3D unit vector of the IMU positions and the gravity vector were computed, using a common reference for all the IMUs. For all trials, the angle computations were filtered with a fourth-order Butterworth low-pass filter, with a 6 Hz cutoff frequency. To keep only the stabilized swimming sequences, two cycles at the beginning and one at the end of the 50 m bouts were systematically removed from the swimming pool analyses. Similarly, the first ten cycles were removed from the analyses conducted in the swimming flume. For each participant, the number of analyzed cycles in the flume was then matched to the number of cycles performed in the swimming pool (among all conditions, this number ranged between 10 and 16).

Determination of stroke time and stroke rate

Stroke times were obtained identifying the absolute time separating two water hand entries. The inverse of stroke time values corresponded to stroke rate (SR). Absolute stroke times were then time-normalized (i.e., a complete cycle was 100%).

In order to characterize the range of the swimmers’ motor repertoire, we computed an index from maximal and minimal SR values of each participant averaged over swimmers sample and compared between the two swimming environments:

$$\mathit{Range\ of\ motor\ repertoire} = \sum_{i=1}^{n}\left(\frac{SR_{\max(i)} - SR_{\min(i)}}{n}\right)$$

with SR_{max} and SR_{min} maximal and minimal values of SR for each participant and in each environment, respectively; and *n* the number of swimmers.

Cycle phases

The front crawl cycle can be divided into four phases (i.e., catch and glide, pull, push and recovery) according to Chollet et al. (2000). We replicated the procedure described in Guignard et al. (2017) to determine the beginning of these four phases. Duration of each stroke phase was then expressed as a percentage of the cycle duration.

Coordination between the upper limbs: the Index of Coordination

From the determination of each stroke phase start, we computed the IdC (Chollet et al., 2000) that attests from the coordination level between both upper limbs during front crawl swimming. Precisely, this computation seeks to determinate the latency time that may appear between two propulsive actions of the upper limbs (latency time LT1 when the right upper limb is considered as the reference, LT2 for the left body side):

$$IdC = \left(\left(\frac{LT1 + LT2}{2} \right) / stroke\_time \right) \times 100$$

Such latency times have been computed from the end of the push of the first upper limb and the beginning of the pull of the second upper limb. This duration was then expressed as a function of the cycle duration to compute the IdC (in %). Once IdC values were obtained, the corresponding ranges of swimmers' motor repertoire were computed in both environments.

Inter-segmental upper limb coordination: coupling angles

The computations of coupling angles were replicated from those performed in Guignard et al. (2017) study (Figure 1), following accurately the procedure described by Needham, Naemi, & Chockalingam (2014). Such an analysis allows the determination of four coordination patterns (i.e., in-phase, anti-phase, distal or proximal), which helped to know how each segment composing the upper limb coordinated itself with its surrounding (hand vs.

lower arm and lower arm vs. upper arm). To quantify the occurrence of each coordination pattern over the entire cycle and over each stroke phase, the frequency of appearance was computed and was reported in percentage (100% symbolizing the exclusive use of a single coordination pattern over the whole duration of the cycle/stroke phase).

Mathematic models

Bideault, Hérault, & Seifert (2013) and Seifert et al. (2015) highlighted that coordination dynamics as a function of speed increase may be modeled using a quadratic approach for populations of expert swimmers. Therefore, second-order polynomial individual mathematic models were retained to fit experimental data in the current study.

Stroke rate dynamics

According to the work of Hay (2002), we modeled SR values as a function of the swimming speed increase for all conditions. This second-order polynomial model is defined by the following mathematical equation, $y = ax^2 + bx + c$ with *a*, *b* and *c* the model constants determined thanks to MATLAB, minimizing by successive iterations the squared of the residuals between the model and the experimental values. *y* corresponding to the SR values (in Hz), and *x* corresponding to the absolute values of swimming speed (i.e., in m/s).

Dynamics of the upper limbs coordination indexes

The same polynomial model was used to characterize the apparition frequency of each four coordination patterns. Therefore *y* now corresponds to the number of occurrences of in-phase, anti-phase, proximal or distal coordination patterns. Polynomial models were tested on these occurrences at the scale (i) of the cycle and (ii) of the stroke phases. Lastly, this model was used to characterize the dynamics of the IdC as a function of the manipulated constraints (i.e., *y* were IdC values in % and *x* the swimming speeds, in m/s).

Accuracy of models as a function of experimental values

To test for the accuracy of our models, we computed the coefficient of determination

(r^2) and the sum of squared errors (SSE):

$$SSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i^2 \times a + x_i \times b + c)^2$$

with *a*, *b* and *c* the polynomial model constants; *i* the first speed and *n* the highest speed. The higher this sum, the higher the distance between values obtained from the experiment and the model. SSE is expressed in the unit of the modeled variables (e.g., Hz for the SR values).

Statistical analyses

All tests were performed with SPSS software (SPSS Statistics 21.0, IBM, Chicago, IL, USA), with a significance level fixed at p <.05. The normality of the distribution (Shapiro-Wilk test) and the variance homogeneity (Levene's test) were checked. When the sphericity (Mauchly test) was significant, the Greenhouse-Geisser correction was applied. Effect size was estimated from partial eta squared (η^2_p) statistics (see Cohen, 1988).

Statistical analysis was conducted through a two-way (2 environments [pool/flume] × 8 speeds [S1 to S8]) repeated measures analysis of variance (ANOVA) on (i) occurrences of the four coordination patterns for hand/lower arm and lower/upper arm couplings at the scale of the cycle and the stroke phases and (ii) IdC values, considered as dependent variables. A one-way repeated measures ANOVA (pool/flume) tested for differences in SR and IdC values based on the computation of (i) the range of motor repertoire and (ii) the constants *a* and *b* of the polynomial models. To detect significant differences among the means of the factors (environments and speeds) and their interactions, the Bonferroni method was used for all post hoc comparisons. When samples did not follow the assumption of normality, or displayed variance heterogeneity, we used non-parametric statistics (Friedman's ANOVAs with Wilcoxon signed-rank tests as *post hoc*).

Results

Effects of constraints on cycle and stroke phase durations

The task constraint manipulation induced a general decrease of the stroke time in both environments (Table 1). This corresponded to a logical increase of SR since it is computed as the reverse of the stroke time (Figure 2, left). On average, the speed increase was also responsible for (i) a decrease of catch and glide duration, (ii) an increase of the pull and push durations (i.e., propulsive phases) and (iii) a general stabilization of the recovery duration. Moreover, the cycle duration was on average significantly longer in the flume compared to the pool, except for S1, S3 and S5 (Table 1). This environmental constraint had a limited impact on the duration of the cycle phases. For instance, we noted that the catch and glide duration remained stable in the flume (27.0 ± 7.1% and 28.7 ± 5.9% at the slowest and highest speeds, respectively), whereas it strongly decreased in the pool with the speed increase (from 33.4 ± 7.4% to 22.5 ± 5.2% of the total stroke duration). The environmental constraint finally highlighted that the proportion of non-propulsive phases (catch and glide + recovery) diminished with the increase of speed in the pool, whereas they were stabilized or even increased in the flume.

Average stroke rate (SR) and index of coordination (IdC) values

The SR increase was steepest in the pool than in the flume for all swimmers, leading to significant lower SR values for S4 and for the three highest swimming speeds in the pool.

IdC values were strongly impacted by the increase of swimming speed: $F(2.49,17.40)=8.80$, $p=0.001$, $\eta^2_p=0.557$. Manipulating the environment led to a strong increase of averaged IdC values in the pool whereas they remained stabilized in the flume (Figure 2, right). IdC values were likewise sensible to the interaction effect between the speed increase and the manipulation of the swimming environment: $F(7,49)=12.44$, $p=0.000$, $\eta^2_p=0.640$. This interaction effect was mainly visible for similar intensities; in particular, IdC was lower in the pool than in the flume at the first and third bouts whereas IdC was higher in the pool than in the flume at the eighth bout.

Individual dynamics of SR and IdC as a function of constraints manipulation

Second-order polynomial models fitted accurately the individual experimental data of SR vs. absolute swimming speed increase (Figure 3A), since the lowest coefficient of determination was 0.82 (swimmer 3 in the pool). To go further, manipulating the fluid flow did not significantly impact the polynomial model constants *a* and *b*: F(1,7)=0.68, p=0.436, η^2_p=0.089 and F(1,7)=1.56, p=0.251, η^2_p=0.183, respectively. In contrast, this constraint revealed that the range of the swimmers' motor repertoire in the flume was 48.4% lower than in the pool, regarding SR values: F(1,7)=85.26, p=0.000, η^2_p=0.924.

The important dispersion of IdC values led to a lower accuracy of the second-order polynomial model (the slowest r^2 was 0.09) as a function of swimming speed increase (Figure 3B). Once again, manipulating the environment did not significantly impact polynomial model constants (*a* and *b*): F(1,7)=4.21, p=0.079, η^2_p=0.376 and F(1,7)=3.94, p=0.088, η^2_p=0.360, respectively. Lastly, the range of swimmers' motor repertoire computed from IdC values in the flume represented only 44.7% of the value observed in the pool: F(1,7)=39.42, p=0.000, η^2_p=0.849.

Inter-segmental coordination of the upper limbs (coupling angle)

At the scale of the cycle, the speed increase mainly influenced the occurrences of the coordination patterns used for the coupling between the lower and the upper arm (Table 2). The interaction effect between the two manipulated constraints was responsible for changes in occurrences of the in-phase and anti-phase coordination patterns used between the hand and the lower arm. At the slowest swimming speeds, in-phase coordination patterns occurred more often in the flume than in the pool, whereas anti-phase coordination patterns were less recurrent in the flume. Interestingly, all these effects are inversed at high speeds (Table 2).

When similar analyses are performed at the scale of each stroke phase, the swimming speed increase impacted the occurrence of the four coordination patterns. However, such an effect was fairly distributed between in-phase, anti-phase, proximal and distal modes.

Discussion

In this study, we sought to determine whether the increases in swimming speed and swimming environment manipulations would destabilize and/or reorganize low- and high-order variables that define the motor repertoire of expert swimmers. To achieve this objective, we analyzed more than 3010 cycles.

Swimming in a pool and a flume: behavioral similarities and differences

The increase in swimming speed resulted in a gradual decrease in mean cycle durations for all swimmers in the two swimming environments. For each individual, these dynamics were accurately characterized in the pool and the flume by second-order polynomial modeling of the stroke rate values (no environmental effect on the ordinates at the origin and the directive coefficients of the slope), echoing previous investigations (Bideault et al., 2013; Hay, 2002; Seifert & Chollet, 2009). The coordination variables also presented individual dynamics of the IdC values evolving according to second-order polynomial modeling for the two flow conditions (no significant difference). The present contribution corroborated the results by Bideault et al. (2013) and Seifert and Chollet (2009) obtained in the pool, but brought new insights into the dynamics of the IdC observed in a resistive environment (flume). To face these constraints –potentiated by speed increase–, individuals adapted their coordination. By comparing similar efforts (i.e., no correspondence between absolute swimming speeds in both environments, but similar relative speeds according to the maximal speed achieved in each environment), we observed a progressive increase of the occurrence of the in-phase coordination pattern for lower/upper arm coupling, whereas the occurrence of the three other patterns (anti-phase, distal or proximal) progressively decreased with speed increase in the flume. These dynamics revealed the emergence of a limited dissociation between the two segments in order to cope with the highest resistances in the two environments.

However, the effect of the swimming environments on these trials performed at similar efforts had a different impact on the SR dynamics, which presented a steeper slope in the pool that could be interpreted as the increased flexibility of this low-order parameter. With SR increase in the flume, the absolute mean duration of entry and glide decreased while the duration of the recovery increased. Indeed, the forward extension of the upper limbs is made against the fluid movement, shortening the beginning of their path. Later in the cycle, the moving fluid strongly pushes the upper limbs backward (Monteil [1992] noted that underwater hand speeds are higher in the flume than the pool). In the pool, positioning the upper limb from the start of the cycle is less constrained due to the progression through a quasi-static environment: it is then easier to adapt the time spent in pull and push phases in order to control coordination (according to Chollet et al. [2000]). Modifications of the beginnings of these stroke phases led to greater range of IdC values used to progress in the pool (the dynamics corresponding to a mean linear increase), moving from catch-up mode at a slower speed towards a tendency to adopt an opposition coordination mode (or even superposition) at maximum speed. Seifert et al. (2004a; 2004b) came to similar conclusions although the elevation of their IdCs showed a breakpoint from the 100/200 m (IdC values from -10.9% to -7.24% between 3000 and 200 m, then from -3.34% to -0.12% between 100 m and maximum speed; our values started around -13% and finished near -3%). The modifications to this coordination mode were much more limited in the flume, with an IdC stabilized in catch-up mode throughout the protocol (maintaining the body in a horizontal position, with a larger contribution of the lower limbs in the propulsion). Inter-segmental coordination between the hand and the lower arm was also impacted by the flume, which made it more difficult to sustain in-phase coordination with the increase in flow speed (contrary to a larger use of anti-phase pattern). Swimming in the pool systematically showed opposite effects, with the predominant results being the increase in in-phase coordination and the appearance of a range of hand/lower arm coordination patterns that may facilitate the development of propulsive forces.

The swimmers' behavioral flexibility was estimated by calculating the range of the motor repertoire, which was systematically more restricted in the flume for low- (SR) and high-order (IdC) variables of behavior. Specifically, these values reached only 51.6 and 44.7% of those observed in the pool, reflecting a narrowest range of potential behaviors in the flume (i.e., swimmer had less action possibilities to perform the task and motor pattern adoptions are mainly linked to the presence of the moving body of water). These behavioral differences in the two environments showed that opportunities for action (i.e., Gibson's affordances, [1979]) were not strictly identical when the fluid was quasi-static (swimming pool) or in motion (flume): swimmers mainly undergone the fluid flow in the flume, whereas they are freer to position their segments in the pool. These differences due to flow that change the landscape of affordances in which the swimmer evolves, prompt the selection of the relevant affordances in a state of *embodied readiness for action* (Rietveld & Kiverstein, 2014). In other words, this embodied readiness for action corresponds to a psychological state in which the coordinative behavior emerged as a reaction to solicitations of objects or events (in our study, the fluid flow) that are meaningful to what the individual's currently cares about (Frijda, 2007). Through this state, individuals are drawn to (i) successfully reach the task goal and (ii) deal with the specificities of the environment in which they are acting (e.g., in our research, the flume gradually prompts the swimmer to stop using the in-phase coordination mode between the hand and lower arm, due to a constraining fluid flow).

Environmental and task constraints explain these behavioral differences

Manipulating the swimming speed (independent variable) revealed different upper limb coordination modes (dependent variable), by showing a transition from catch-up to opposition or even superposition. Therefore, external constraints bounded the behavior of the swimmers, without prescribing it, since two swimmers from similar level were able to successfully achieve the task goal without using the same coordination mode (e.g., either catch-up or opposition modes at S8 in the pool). The emergence of new coordination mode (i.e., opposition or superposition) revealed that swimmers are particularly constrained by the hydrodynamic resistances, which increase with the speed square during aquatic locomotion (Zamparo et al., 2009). This modification in technique can be taken as an emergent behavior to face strong wave drag (maximum drag from 1.7-1.8 m/s [Toussaint et al., 2000] to the highest swimming speeds in a pool). A future investigation would be to investigate these levels of absolute speeds in the flume, to indicate if those results may be replicated in this dynamic environment.

According to Seifert et al. (2004b), however, these changes in coordination are not only due to the increase in swimming speed, but also to the specificities of the environment in which the movement takes place. In the flume, the mass of water is moving backwards, whatever the swimming speed: the changes in phase durations are therefore more difficult to achieve because they require a fine spatial-temporal coordination hardly sustainable in a dynamic environment (for this reason, IdC variations remained in catch-up). The increase in speed –associated with the swimmer's movements– also had a completely different impact in the two environments since the movement of each water particle becomes unpredictable and chaotic in the flume, indicating a high degree of turbulence (Kundu et al., 2012). Moreover, we observed a high amount of air entrained into the flow with speed increase, which may also affect the swimmer's buoyancy. These air bubbles trapped in the water, coupled to the size and design of the flume used in our experiment (i.e., short flow channel, few elements to make the fluid laminar, etc.) are additional external parameters that may add constraints on swimming motion (Guignard et al., 2017). Thus, the condition of our most constraining trial definitely corresponds to the highest speeds in the flume. In these configurations, we observed that swimmers did not exhibit greater occurrences of in-phase coordination for the hand and lower arm compared with the pool. To go further, the increases in the occurrences of anti-phase pattern is another evidence that the flume led to a dissociation between hand and lower arm and hence to a lower propulsive continuity in comparison to the pool at similar efforts, as highlighted by the IdC values. Neither ineffective nor detrimental in the dynamic and turbulent flume fluid flow, the emergence of this specific motor coordination should be considered as adapted since swimmers remained at the same position throughout the trial.

The motor coordination in the flume seemed however less flexible than in the pool for the range of speeds tested in the present study. Indeed, whether for the low- or high-order variables of behavior, the constraints of flume swimming restricted the range of the motor repertoires that could be used in this swimming condition. In other words, exploring the perceptual-motor space (Newell, Kugler, van Emmerik, & Mcdonald, 1989) and the opportunities for action in the fluid appeared limited in the flume. The flume therefore no longer acts exclusively as an amplifier of sensations (Guignard et al., 2017), but also as a challenger for upper limb coordination that would help in evaluating the behavioral flexibility of elite swimmers.

Conclusions, limitations and perspectives

When the behavioral dynamics of expert swimmers was compared in a pool and in a flume (by scanning the upper limb coordination at eight different swimming speeds corresponding to similar efforts), obvious differences of coordination occurred between the two environments (dynamic flow towards the swimmers, waves and chaotic movements of water particles). Our study contributes to understand how such behavioral adaptations emerged in the flume: in particular, a reduction of the in-phase coordination pattern and a stabilization of the upper limb coordination in catch-up was observed with speed increase. Therefore, these swimmers were able to more easily exploit the opportunities for action in the pool than in the flume, where motor adjustments emerged by modifying a smaller number of degrees of freedom.

This study could be complemented by research that takes into account a wider range of absolute swimming speeds (here the highest was 1.41 m/s in the flume), which would account for the transition from catch-up to opposition or even superposition; however, it must be kept in mind that low number of cycles could be performed at high speed, which can affect representativeness of the motor repertoire. It is also important to consider that in our study, absolute swimming speeds differed between pool and flume for a given bout because swimmers were not able to achieve similar maximal swimming speeds in both environments. Therefore, comparisons between the two environments concerned similar efforts and considered similar relative speeds. However, to overcome this limitation, we modeled the coordination dynamics in both environments by polynomial functions in order to compare those modeling.

Although the IdC computation is based on the time gap between the propulsive phases, the effectiveness of the propulsion during those phases was not checked by forces data or instantaneous speed transferred to the body. Moreover, the IdC computation considered pull and push phases on the basis of the action-reaction principle (Newton's laws) but did not take into account the possible contribution of lift forces generated by sculling movement. Those limitations recall that the IdC remains an index of coordination and not of propulsion. Since the tests were systematically conducted in the pool before the flume, we may finally observe a possible order effect between the two tested situations. Last, the contribution of the leg kicking was not investigated but should not be ignored, as recently highlighted by Guignard et al. (in press).

What does this article add?

Our study highlighted that moving through water should not be exclusively viewed as analyses in a quasi-static environment corresponding to swimming in a pool. Rather, one should consider that competitive swimming (e.g., swimming fast in a pool) is only a part of the water competence (Stallman, Moran, Quan, & Langendorfer, 2017) necessary to an individual to move comfortably (achieving both performance and safety) in the aquatic environment. Water competence is more inclusive as it regroups safe entry and exit, breath control, stationary surface, water orientation, propulsion, personal flotation device (e.g., lifejacket), clothed water, open water, knowledge of local hazards, coping with risk, rescue and water safety competences (Stallman et al., 2017). By simulating a dynamic fluid flow thanks to the flume (i.e., similar to water motion in a river or in the sea), we highlighted a complete motor reorganization that did not fully correspond to swimming skills taught by coaches to swim in pool. Specifically, the significant reduction of the range of the motor repertoire obtained after a scanning task performed in the flume revealed that aquatic skills couldn’t be developed or reinforced without being connected to the swimmers’ surrounding environment, since possibilities for action always emerged relative to this specific environment. In this sense, flume training would be particularly interesting for individuals training and competing in open water sports (e.g., triathlon), since swimmers must cope with surrounding constraints of dynamic and turbulent flow, generally related to close grouping of swimmers and the natural environment in which they are evolving.

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Tables

Table 1: Results of the statistical analysis regarding the stroke time (s) and the duration of each stroke phase (in % of the total stroke time) for the eight swimming speeds on the right body side.

Variables	Stroke time (s)		Catch and glide (%)		Pull (%)		Push (%)		Recovery (%)	
	Pool	**Flume**	**Pool**	**Flume**	**Pool**	**Flume**	**Pool**	**Flume**	**Pool**	**Flume**
Mean S1	2.14	2.11	**33.4***	27.0	**23.1***	26.4	14.5	16.0	29.0	30.6
SD S1	0.24	0.23	**7.4**	7.1	**4.3**	6.4	4.2	4.5	3.7	2.7
Mean S2	**1.96***	2.07	29.8	28.6	**23.6***	26.9	15.0	14.9	31.6	29.6
SD S2	**0.17**	0.21	7.8	4.9	**3.5**	4.7	5.1	3.6	3.8	2.3
Mean S3	1.94	1.96	31.0	29.0	24.6	26.9	15.4	15.3	29.0	28.9
SD S3	0.13	0.25	7.7	5.7	4.9	5.1	4.6	4.0	3.2	2.4
Mean S4	**1.72***	1.87	**26.9***	29.9	26.4	25.9	**16.1***	15.3	30.6	29.0
SD S4	**0.13**	0.20	**6.8**	4.8	4.2	4.1	**4.6**	4.4	3.3	2.9
Mean S5	1.72	1.78	26.6	27.1	26.6	27.3	16.3	16.1	30.5	29.5
SD S5	0.12	0.20	7.0	6.2	4.8	4.8	4.7	4.2	3.9	2.3
Mean S6	**1.52***	1.72	25.9	27.5	26.1	26.3	17.5	16.1	30.5	30.1
SD S6	**0.65**	0.16	6.3	6.5	3.9	5.0	4.9	4.2	4.0	2.2
Mean S7	**1.55***	1.62	25.3	27.7	26.9	26.8	**17.4***	15.7	30.5	29.8
SD S7	**0.10**	0.14	7.0	6.4	4.2	5.3	**4.2**	3.7	3.9	3.2
Mean S8	**1.36***	1.68	**22.5***	28.7	**28.0***	22.3	18.8	17.0	30.8	32.0
SD S8	**0.04**	0.02	**5.2**	5.9	**4.7**	3.8	4.2	5.3	3.2	4.4
Speed effect	$\chi^2(8)$ = 53.08, $p < .05$	$\chi^2(8)$ = 46.29, $p < .05$	$\chi^2(8)$ = 37.54, $p < .05$	*no*	$\chi^2(8)$ = 18.07, $p < .05$	*no*	$\chi^2(8)$ = 41.34, $p < .05$	*no*	*no*	$\chi^2(8)$ = 14.38, $p < .05$

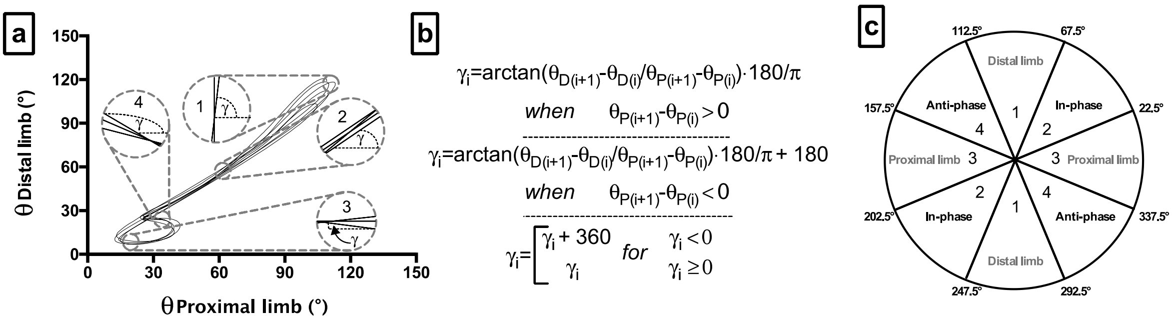
Note: SD: standard deviation; *****: significant difference with flume swimming; χ^2: Friedman's test. Significant at p<.05.

Table 2: Results of two-ways repeated ANOVAs performed over the percentage of apparition of the four coordination patterns at the scale of the cycle (inter-segmental upper limb coordination).

	Coordination patterns	Proximal	In-phase	Distal	Anti-phase
Hand/lower arm	Speed effect	***F*(7,7)=7.373, *p*=0.009, η_p^2=0.881** (12.8 ± 0.2% at V1 and 13.0 ± 1.7 % at V8)	*N.S.* (*p*=0.165)	*N.S.* (*p*=0.106)	*N.S.* (*p*=0.229)
	Environmental effect	*N.S.* (*p*=0.998)	*N.S.* (*p*=0.891)	*N.S.* (*p*=0.302)	*N.S.* (*p*=0.125)
	Interactions	***F*(7,7)=6.740, *p*=0.011, η_p^2=0.871** (pool: 13.2 ± 2.8% at V1 and 6.3 ± 1.9 % at V8; flume: 12.3 ± 3.2% at V1 and 19.6 ± 5.3 % at V8)	***F*(7,7)=5.615, *p*=0.018, η_p^2=0.849** (pool: 64.3 ± 0.2% at V1 and 83.1 ± 4.3 % at V8; flume: 68.0 ± 7.7% at V1 and 63.4 ± 3.9 % at V8)	*N.S.* (*p*=0.303)	***F*(7,7)=6.158, *p*=0.014, η_p^2=0.860** (pool: 4.9 ± 0.1% at V1 and 3.0 ± 0.7 % at V8; flume: 4.7 ± 1.8% at V1 and 10.4 ± 1.0 % at V8)
Lower arm/upper arm	Speed effect	***F*(7,14)=10.757, *p*=0.000, η_p^2=0.843** (18.8 ± 2.2% at V1 and 7.5 ± 0.6 % at V8)	***F*(7,14)=28.958, *p*=0.000, η_p^2=0.935** (57.4 ± 5.0% at V1 and 80.3 ± 4.3 % at V8)	***F*(7,14)=6.598, *p*=0.001, η_p^2=0.767** (16.1 ± 1.8% at V1 and 8.6 ± 2.6 % at V8)	***F*(7,14)=7.064, *p*=0.001, η_p^2=0.779** (7.7 ± 1.9% at V1 and 3.6 ± 1.3 % at V8)
	Environmental effect	*N.S.* (*p*=0.249)	*N.S.* (*p*=0.808)	*N.S.* (*p*=0.757)	*N.S.* (*p*=0.374)
	Interactions	*N.S.* (*p*=0.669)	*N.S.* (*p*=0.493)	*N.S.* (*p*=0.273)	*N.S.* (*p*=0.493)

Note: N.S.: non-significant; in bold significant results at *p*<.05.

Figures



$$\gamma_i=\arctan(\theta_{D(i+1)}-\theta_{D(i)}/\theta_{P(i+1)}-\theta_{P(i)})\cdot 180/\pi \quad \textit{when} \quad \theta_{P(i+1)}-\theta_{P(i)}>0$$

$$\gamma_i=\arctan(\theta_{D(i+1)}-\theta_{D(i)}/\theta_{P(i+1)}-\theta_{P(i)})\cdot 180/\pi+180 \quad \textit{when} \quad \theta_{P(i+1)}-\theta_{P(i)}<0$$

$$\gamma_i=\left[\begin{array}{lcl}\gamma_i+360 & \textit{for} & \gamma_i<0\\ \gamma_i & & \gamma_i\geq 0\end{array}\right.$$

Figure 1: Three steps (a to c) to compute and interpret coupling angles values. (a) Four zooms performed on an angle-angle plot of the right hand vs. right lower arm angles. Coupling angle (γ_i) is defined as the angle between the horizontal and the trajectory of the angle-angle plot between i and i + 1 instants (see [b] for rules of computation). (c) As a function of the value of the angle, four different coordination patterns between the two limbs may be determined (from 1, distal: variation of the angle of the distal limb without modification of the angle of the proximal limb to 4, anti-phase: when the angle of one limb varies, the angle of the other limb varies in an opposite way). Procedure extensively described by Needham, Naemi, & Chockalingam (2014).

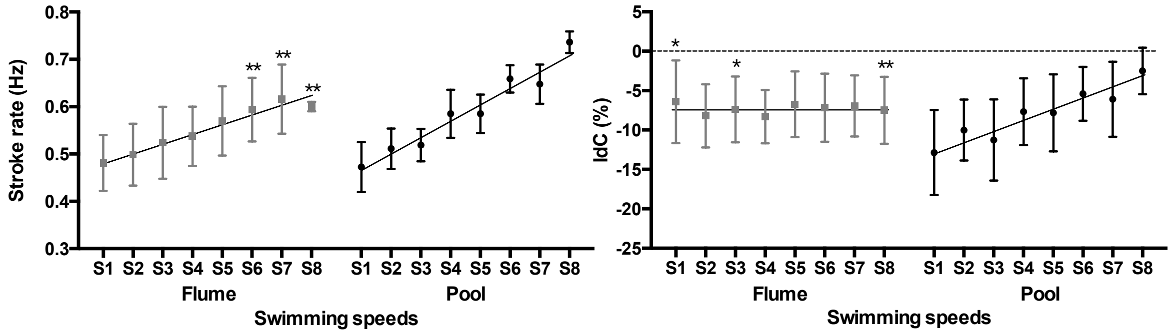


Figure 2: Mean ± SD of SR (left) and IdC (right) values as a function of swimming speed increase in both environments (flume in gray, pool in black) and eight swimmers. Linear regressions associated with the dynamics of the data are likewise depicted (black lines). (*) Values significantly higher in comparison to the same swimming speed step in the pool. (**) Values significantly lower in comparison to the same swimming speed step in the pool. $p<.05$.

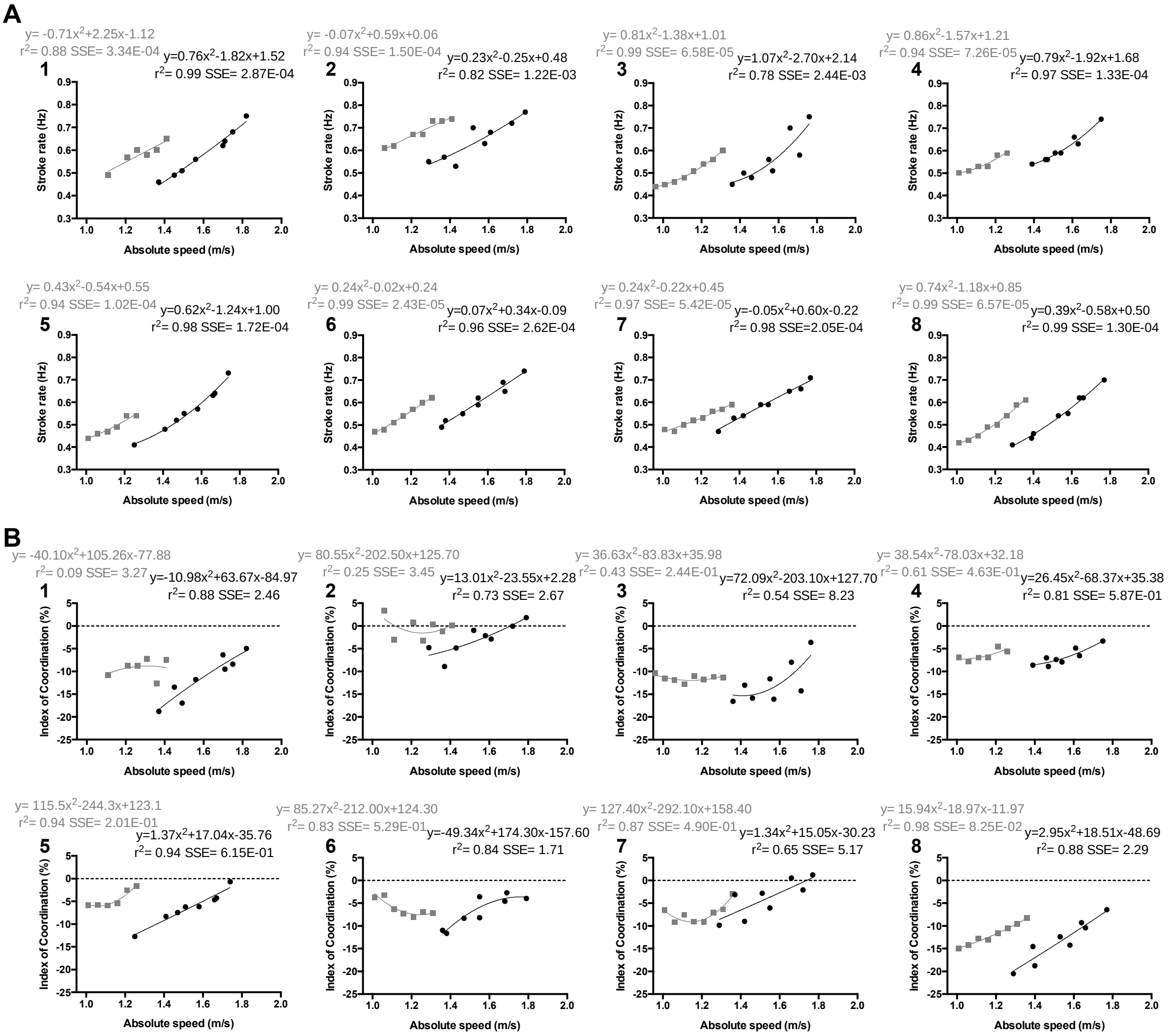


Figure 3: Second-order polynomial models characterizing the dynamics of SR values (A) and IdC values (B) as a function of swimming speed increase for the eight swimmers (graphs numbered from 1 to 8) and for both swimming environments (flume in gray and pool in black). r^2 and SSE (in Hz for SR and in % for IdC) values are displayed to assess for the accuracy of the models.