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**Coordination Dynamics of Upper Limbs in Swimming:  
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GUIGNARD, B., ROUARD, A., CHOLLET, D., BONIFAZI, M., DALLA VEDOVA, D., HART, John <<http://orcid.org/0000-0002-6142-4515>> and SEIFERT, L.

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

3  
4 Running head: Constraint impacts on crawl coordination dynamics

5 **Authors**

6                   Brice Guignard<sup>1,2</sup>, Annie Rouard<sup>2</sup>, Didier Chollet<sup>1</sup>, Marco Bonifazi<sup>3</sup>, Dario Dalla  
7   Vedova<sup>4</sup>, John Hart<sup>5</sup> and Ludovic Seifert<sup>1</sup>

8 <sup>1</sup>Center for the Study and the Transformation of Physical Activities (CETAPS), Faculty of  
9 Sport Sciences, University of Rouen Normandy, UNIROUEN, 76821 Mont Saint Aignan  
10 Cedex, France.           <sup>2</sup>Interuniversity Biology and Motricity Laboratory (LIBM), University  
11 Savoie Mont Blanc, 73376 Le Bourget du Lac Cedex, France.           <sup>3</sup>Department of Medicine,  
12 Surgery, and NeuroScience, University of Siena, Siena, Italy.           <sup>4</sup>Sport            Science  
13 Department. Medicine and Science Sport Institute, Italian National Olympic Committee  
14 (CONI), Rome, Italy.           <sup>5</sup>Centre for Sports Engineering Research, Sheffield Hallam  
15 University, Broomgrove Road, Sheffield S10 2NA, UK.

16 **Corresponding author:** Brice Guignard; Center for the Study and the Transformation of  
17 Physical Activities (CETAPS), Faculty of Sport Sciences, University of Rouen Normandy,  
18 UNIROUEN, 76821 Mont Saint Aignan Cedex, France. Tel: +33 235 14 67 92. e-mail:  
19 [brice.guignard@univ-rouen.fr](mailto:brice.guignard@univ-rouen.fr)

20  
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1 **Abstract**

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

21

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

## Constraint impacts on crawl coordination dynamics

23           According to the ecological dynamics theoretical framework, complex  
24 neurobiological systems (e.g., human behavior) displayed *self-organization* properties  
25 between cells, muscles, bones, and limbs to act functionally in performance environments  
26 (Davids et al., 2013). Self-organization is a concept by which “temporal, spatial or spatial-  
27 temporal patterns evolve without being imposed on the system from the outside” (Haken,  
28 1983; p.56). Moreover, the *emergence* of functional motor behaviors is continuously bounded  
29 by the interactions of three categories of constraints (Newell, 1986). *Environmental*  
30 constraints largely related to the environment in which the task is performed. All individual  
31 characteristics of a performer denoted *organismic* constraints while attributes relative to the  
32 specific goals of an activity are *task* constraints.

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

47           Increasing the movement speed on land does not fundamentally increase the task

## Constraint impacts on crawl coordination dynamics

48 complexity (or the energy requirement to perform the task), whereas this constraint can play a  
49 much more decisive role in other environments. For instance, since water is 800 times denser  
50 than air, every action is performed with very low propelling efficiency (0.5–2.2%) in  
51 comparison to movements performed on dry land (20–25%; [Toussaint, Hollander, van den  
52 Berg, & Vorontsov, 2000]). Additionally, aquatic motricity is generally not performed in a  
53 purely static environment but one that is quasi-static or clearly dynamic that can be  
54 problematic for producing and controlling movement. This was exemplified in swimming by  
55 Cohen, Cleary, and Mason, (2012) during a dolphin kick, with the use of smoothed particle  
56 hydrodynamics: kicks generate fluid structures travelling diagonally up or down away from  
57 the swimmer, but also rotational motion of the particles. It means the fluid may  
58 spontaneously change its state to a fully turbulent flow either due to an increase of its own  
59 velocity or as a function of swimmer's movements. Therefore, the movements of water  
60 particles become incoherent, chaotic, or even unpredictable, notably visible at the surface  
61 (Kundu, Cohen, & Dowling, 2012). At the opposite, quasi-static aquatic environments (or  
62 environments flowing at very slow speeds) present water particles flowing in parallel  
63 streamlines, defined as laminar flow. Moving through the fluid or manipulating the flow  
64 speed directly influences the resistances that an individual is facing, since resistance depends  
65 on the square of the speed of the fluid displacement (Zamparo, Gatta, Pendergast, & Capelli,  
66 2009). Among all constraints surrounding a competitive swimmer, speed of movement and  
67 fluid resistance appear as one of the major biomechanical determinants performers have to  
68 face when they are moving through water.

69 Characterizing the effect of movement speed on coordination dynamics was  
70 extensively tested in front crawl (Chollet, Chabies, & Chatard, 2000; Komar et al., 2012;  
71 Seifert, Boulesteix, & Chollet, 2004a; Seifert, Chollet, & Bardy, 2004b; Seifert, Chollet, &  
72 Rouard, 2007), since swimming speed determines performance. Much of this work focused

73 on the coordination between the upper limbs, by computing the Index of Coordination (IdC)  
74 (Chollet et al., 2000). The IdC assesses the time gap between two propulsive actions based on  
75 kinematic measurements. In those previous works, both the stability (i.e., the persistence of  
76 motor behaviors in response to external constraints) and flexibility (i.e., the range of  
77 individual motor repertoires in given performance situations) of expert behaviors at different  
78 swimming speeds were investigated. Those studies mainly focused on expert swimmers as  
79 behavioral adaptability (as a subtle blend between stability and flexibility, for more details,  
80 see Davids et al., 2013; Seifert, Button & Davids, 2013) reflect the skill of human to exploit  
81 the environmental and organismic resources to reach the task goal. As an example, those  
82 researches reported a spontaneous shift of the IdC values (Seifert et al., 2004a; Seifert et al.,  
83 2004b) from catch-up mode for middle distances towards opposition/superposition  
84 coordination for sprint speeds (superposition indicated an overlap of the propulsive actions of  
85 the two upper limbs; [Komar et al., 2012; Seifert et al., 2007]). Using a protocol to scan all  
86 possible swimmers' behaviors (e.g., by increasing linearly the swimming speed) may conduct  
87 to the spontaneous and non-prescribed emergence of a new coordination mode (Seifert et al.,  
88 2007). Due to the constraints that surround swimming motion, several profiles could be  
89 determined: some swimmers were able to face the constraints but remained not very flexible  
90 (i.e., reaching high swimming speeds by always using the same coordination), whereas others  
91 were highly flexible to reach the task goal (i.e., high swimming speeds with a wide repertoire  
92 of motor solutions: IdC variations) (Bideault et al., 2011). In this sense, the manipulation of  
93 these constraints would be of valuable interest to challenge the swimmers' behaviors, and  
94 more broadly to test for their range of motor repertoire (i.e., action capabilities).

95         The main aim of this study was therefore to scan the coordination dynamics of expert  
96 swimmers as a function of the increase in swimming speed coupled with a manipulation of  
97 their swimming environment (i.e., using a flume [Guignard et al., 2017] *vs.* using a

98 swimming pool). Specifically, we used a scanning task to test the behavioral flexibility in  
99 order to understand whether swimmers were more likely to use a wide motor repertoire  
100 and/or a restricted number of stable states to achieve the task goal (Guignard et al., 2017). We  
101 hypothesized that the flume would narrow the landscape of affordances (Rietveld &  
102 Kiverstein, 2014) (i.e., action possibilities offered by the environment relative to the  
103 swimmer's capabilities) in comparison with swimming in a traditional pool, both in term of  
104 low-order behavioral variables (e.g., stroke rate [Hay, 2002]) and high-order behavioral  
105 variables (e.g., coordination). Indeed, the task goal achievement in the flume is conditioned  
106 by the creation of continuous propulsion to sustain the speed imposed by a turbulent and  
107 wavy fluid flow (e.g., it is hard to glide against the fluid flow in the flume [Guignard et al.,  
108 2017]). For these reasons, swimmers' behavioral adaptations would be mainly visible for  
109 coordination of the upper limbs (due to dynamic fluid flow) but also coordination within the  
110 different segments composing the upper limb (difficulty to position distal extremities).

## 111 **Methods**

### 112 **Participants**

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

### 121 **Set-up**

122 The first part of testing took place in a 50 m indoor swimming pool (in order to set the



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

### 130 **Procedure**

131         After a standard 10 min warm-up performed in the pool, swimmers performed 8×50  
132 m bouts at 76, 80, 84, 88, 92, 96, 100 and 104% of their mean speed as obtained during their  
133 best race time on 200 m front crawl (corresponding to average absolute speeds of 1.33 [speed  
134 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]).  
135 Two experimenters imposed the target speeds, the first acting as a pacer (holding a pole) and  
136 the second controlling the speed at the end of the pool, as extensively described in Guignard  
137 et al. (2017). Without removing their testing equipment, swimmers were immediately  
138 transferred to the swimming flume to commence the same incremental protocol. We  
139 considered that maximal effort during a 200 m front crawl (where 70-90 cycles were  
140 performed in 1 minute 50 seconds to 2 minutes) could be compared to a maximal effort of 1  
141 minute 50 seconds to 2 minutes in the flume. Based on the maximal swimming speed  
142 achieved during swimming 2 minutes at maximal intensity in the flume, relative speeds for  
143 eight bouts at submaximal intensity were computed following the same increments than  
144 previously selected in the swimming pool. Swimmers started the test between 76 to 80 % of  
145 the maximal speed they were able to sustain in the flume. Subsequent trials with 4% intensity  
146 increment were then performed, and the test ended when swimmers finished a trial in the net  
147 behind them. In these conditions, swimmers performed from 6 to 8 trials over forty cycles;

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

#### 159 **Data collection**

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

168 To obtain the sensor orientations in the 3D field, the magnetometers were held above  
169 the pool and the flume for calibration, in order to reduce magnetic distortion during data  
170 processing. Other calibrations (performed during rest periods) maintain alignment of sensor  
171 axes to the anatomical body axes, to obtain analyses that would be insensitive to the IMU  
172 orientations despite the multiple body configurations in the swimmers' sample. Such

173 procedures consisted of sequences of upper limbs movements repeated five times: flexion-  
174 extension around the transversal axis and prono-supination around the longitudinal axis.

### 175 **Data analysis**

176 The data were processed using Matlab r2014a (The MathWorks, Inc. Natick, MA,  
177 USA). To obtain angles from raw data recorded with the IMUs, we used the complementary  
178 filter of Madgwick, Harrison, & Vaidyanathan (2011) in the manner of Guignard et al.  
179 (2017). Segmental angles, or angles between the 3D unit vector of the IMU positions and the  
180 gravity vector were computed, using a common reference for all the IMUs. For all trials, the  
181 angle computations were filtered with a fourth-order Butterworth low-pass filter, with a 6 Hz  
182 cutoff frequency. To keep only the stabilized swimming sequences, two cycles at the  
183 beginning and one at the end of the 50 m bouts were systematically removed from the  
184 swimming pool analyses. Similarly, the first ten cycles were removed from the analyses  
185 conducted in the swimming flume. For each participant, the number of analyzed cycles in the  
186 flume was then matched to the number of cycles performed in the swimming pool (among all  
187 conditions, this number ranged between 10 and 16).

### 188 **Determination of stroke time and stroke rate**

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

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

$$195 \quad \text{Range of motor repertoire} = \sum_{i=1}^n \left( \frac{SR_{\max(i)} - SR_{\min(i)}}{n} \right)$$

196 with  $SR_{\max}$  and  $SR_{\min}$  maximal and minimal values of SR for each participant and in each

197 environment, respectively; and  $n$  the number of swimmers.

### 198 **Cycle phases**

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

### 203 **Coordination between the upper limbs: the Index of Coordination**

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

$$209 \quad IdC = \left( \left( \frac{LT1 + LT2}{2} \right) / stroke\_time \right) \times 100$$

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

### 215 **Inter-segmental upper limb coordination: coupling angles**

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

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

### 225 **Mathematic models**

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

### 230 **Stroke rate dynamics**

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

### 237 **Dynamics of the upper limbs coordination indexes**

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

### 244 **Accuracy of models as a function of experimental values**

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

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

$$247 \quad SSE = \frac{1}{n} \sum_{i=1}^n (y_i - x_i^2 \cdot a + x_i \cdot b + c)^2$$

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

## 251 **Statistical analyses**

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

257 Statistical analysis was conducted through a two-way (2 environments [pool/flume]  $\times$   
258 8 speeds [S1 to S8]) repeated measures analysis of variance (ANOVA) on (i) occurrences of  
259 the four coordination patterns for hand/lower arm and lower/upper arm couplings at the scale  
260 of the cycle and the stroke phases and (ii) IdC values, considered as dependent variables. A  
261 one-way repeated measures ANOVA (pool/flume) tested for differences in SR and IdC  
262 values based on the computation of (i) the range of motor repertoire and (ii) the constants  $a$   
263 and  $b$  of the polynomial models. To detect significant differences among the means of the  
264 factors (environments and speeds) and their interactions, the Bonferroni method was used for  
265 all post hoc comparisons. When samples did not follow the assumption of normality, or  
266 displayed variance heterogeneity, we used non-parametric statistics (Friedman's ANOVAs  
267 with Wilcoxon signed-rank tests as *post hoc*).

## 268 **Results**

### 269 **Effects of constraints on cycle and stroke phase durations**

270 The task constraint manipulation induced a general decrease of the stroke time in both

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

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

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

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

### 295 **Individual dynamics of SR and IdC as a function of constraints manipulation**

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

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

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

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

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



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## Discussion

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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.

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

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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.

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

371 the appearance of a range of hand/lower arm coordination patterns that may facilitate the  
372 development of propulsive forces.

373         The swimmers' behavioral flexibility was estimated by calculating the range of the  
374 motor repertoire, which was systematically more restricted in the flume for low- (SR) and  
375 high-order (IdC) variables of behavior. Specifically, these values reached only 51.6 and  
376 44.7% of those observed in the pool, reflecting a narrowest range of potential behaviors in the  
377 flume (i.e., swimmer had less action possibilities to perform the task and motor pattern  
378 adoptions are mainly linked to the presence of the moving body of water). These behavioral  
379 differences in the two environments showed that opportunities for action (i.e., Gibson's  
380 affordances, [1979]) were not strictly identical when the fluid was quasi-static (swimming  
381 pool) or in motion (flume): swimmers mainly undergone the fluid flow in the flume, whereas  
382 they are freer to position their segments in the pool. These differences due to flow that  
383 change the landscape of affordances in which the swimmer evolves, prompt the selection of  
384 the relevant affordances in a state of *embodied readiness for action* (Rietveld & Kiverstein,  
385 2014). In other words, this embodied readiness for action corresponds to a psychological state  
386 in which the coordinative behavior emerged as a reaction to solicitations of objects or events  
387 (in our study, the fluid flow) that are meaningful to what the individual's currently cares  
388 about (Frijda, 2007). Through this state, individuals are drawn to (i) successfully reach the  
389 task goal and (ii) deal with the specificities of the environment in which they are acting (e.g.,  
390 in our research, the flume gradually prompts the swimmer to stop using the in-phase  
391 coordination mode between the hand and lower arm, due to a constraining fluid flow).

### 392 **Environmental and task constraints explain these behavioral differences**

393         Manipulating the swimming speed (independent variable) revealed different upper  
394 limb coordination modes (dependent variable), by showing a transition from catch-up to  
395 opposition or even superposition. Therefore, external constraints bounded the behavior of the

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

406         According to Seifert et al. (2004b), however, these changes in coordination are not  
407 only due to the increase in swimming speed, but also to the specificities of the environment in  
408 which the movement takes place. In the flume, the mass of water is moving backwards,  
409 whatever the swimming speed: the changes in phase durations are therefore more difficult to  
410 achieve because they require a fine spatial-temporal coordination hardly sustainable in a  
411 dynamic environment (for this reason, IdC variations remained in catch-up). The increase in  
412 speed –associated with the swimmer’s movements– also had a completely different impact in  
413 the two environments since the movement of each water particle becomes unpredictable and  
414 chaotic in the flume, indicating a high degree of turbulence (Kundu et al., 2012). Moreover,  
415 we observed a high amount of air entrained into the flow with speed increase, which may also  
416 affect the swimmer’s buoyancy. These air bubbles trapped in the water, coupled to the size  
417 and design of the flume used in our experiment (i.e., short flow channel, few elements to  
418 make the fluid laminar, etc.) are additional external parameters that may add constraints on  
419 swimming motion (Guignard et al., 2017). Thus, the condition of our most constraining trial  
420 definitely corresponds to the highest speeds in the flume. In these configurations, we

421 observed that swimmers did not exhibit greater occurrences of in-phase coordination for the  
422 hand and lower arm compared with the pool. To go further, the increases in the occurrences  
423 of anti-phase pattern is another evidence that the flume led to a dissociation between hand  
424 and lower arm and hence to a lower propulsive continuity in comparison to the pool at similar  
425 efforts, as highlighted by the IdC values. Neither ineffective nor detrimental in the dynamic  
426 and turbulent flume fluid flow, the emergence of this specific motor coordination should be  
427 considered as adapted since swimmers remained at the same position throughout the trial.

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

### 437                                   **Conclusions, limitations and perspectives**

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

446 pool than in the flume, where motor adjustments emerged by modifying a smaller number of  
447 degrees of freedom.

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

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

469 **What does this article add?**

470 Our study highlighted that moving through water should not be exclusively viewed as

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

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570 **Tables**

Constraint impacts on crawl coordination dynamics

571 Table 1: Results of the statistical analysis regarding the stroke time (s) and the duration of each  
572 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	<b>33.4*</b>	27.0	<b>23.1*</b>	26.4	14.5	16.0	29.0	30.6
SD S1	0.24	0.23	<b>7.4</b>	7.1	<b>4.3</b>	6.4	4.2	4.5	3.7	2.7
Mean S2	<b>1.96*</b>	2.07	29.8	28.6	<b>23.6*</b>	26.9	15.0	14.9	31.6	29.6
SD S2	<b>0.17</b>	0.21	7.8	4.9	<b>3.5</b>	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	<b>1.72*</b>	1.87	<b>26.9*</b>	29.9	26.4	25.9	<b>16.1*</b>	15.3	30.6	29.0
SD S4	<b>0.13</b>	0.20	<b>6.8</b>	4.8	4.2	4.1	<b>4.6</b>	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	<b>1.52*</b>	1.72	25.9	27.5	26.1	26.3	17.5	16.1	30.5	30.1
SD S6	<b>0.65</b>	0.16	6.3	6.5	3.9	5.0	4.9	4.2	4.0	2.2
Mean S7	<b>1.55*</b>	1.62	25.3	27.7	26.9	26.8	<b>17.4*</b>	15.7	30.5	29.8
SD S7	<b>0.10</b>	0.14	7.0	6.4	4.2	5.3	<b>4.2</b>	3.7	3.9	3.2
Mean S8	<b>1.36*</b>	1.68	<b>22.5*</b>	28.7	<b>28.0*</b>	22.3	18.8	17.0	30.8	32.0
SD S8	<b>0.04</b>	0.02	<b>5.2</b>	5.9	<b>4.7</b>	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;  $\chi^2$ : Friedman's test. Significant at  $p < .05$ .

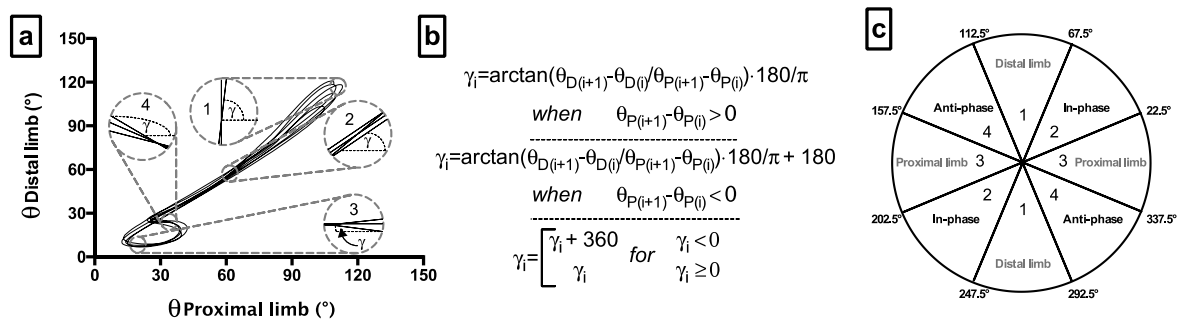
573 Table 2: Results of two-ways repeated ANOVAs performed over the percentage of apparition of the  
574 four coordination patterns at the scale of the cycle (inter-segmental upper limb coordination).  
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Coordination patterns	Proximal	In-phase	Distal	Anti-phase	
Hand/lower arm	Speed effect	<b><math>F(7,7)=7.373,</math> <math>p=0.009,</math> <math>\eta_p^2=0.881</math></b> (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	<b><math>F(7,7)=6.740,</math> <math>p=0.011,</math> <math>\eta_p^2=0.871</math></b> (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)	<b><math>F(7,7)=5.615,</math> <math>p=0.018,</math> <math>\eta_p^2=0.849</math></b> (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. ( $p=0.303$ )	<b><math>F(7,7)=6.158,</math> <math>p=0.014,</math> <math>\eta_p^2=0.860</math></b> (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	<b><math>F(7,14)=10.757,</math> <math>p=0.000,</math> <math>\eta_p^2=0.843</math></b> (18.8 ± 2.2% at V1 and 7.5 ± 0.6 % at V8)	<b><math>F(7,14)=28.958,</math> <math>p=0.000,</math> <math>\eta_p^2=0.935</math></b> (57.4 ± 5.0% at V1 and 80.3 ± 4.3 % at V8)	<b><math>F(7,14)=6.598,</math> <math>p=0.001,</math> <math>\eta_p^2=0.767</math></b> (16.1 ± 1.8% at V1 and 8.6 ± 2.6 % at V8)	<b><math>F(7,14)=7.064,</math> <math>p=0.001,</math> <math>\eta_p^2=0.779</math></b> (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  $p < .05$ .

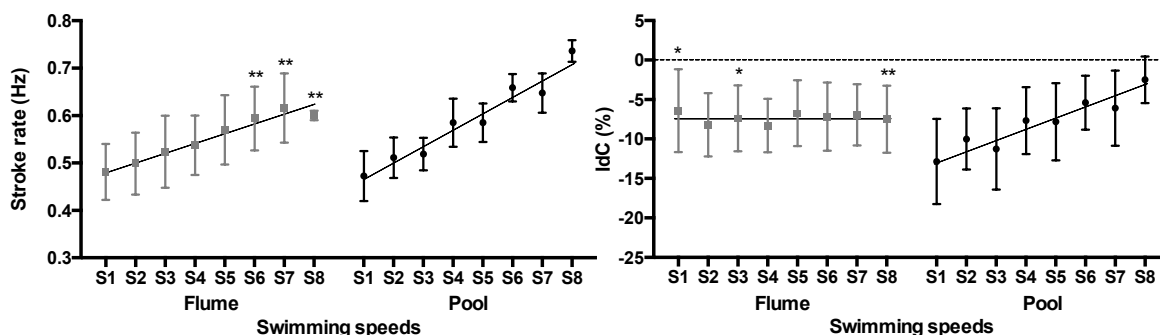
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580 **Figures**



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582 Figure 1: Three steps (a to c) to compute and interpret coupling angles values. (a) Four zooms  
 583 performed on an angle-angle plot of the right hand vs. right lower arm angles. Coupling angle ( $\gamma_i$ ) is  
 584 defined as the angle between the horizontal and the trajectory of the angle-angle plot between  $i$  and  
 585  $i + 1$  instants (see [b] for rules of computation). (c) As a function of the value of the angle, four different  
 586 coordination patterns between the two limbs may be determined (from 1, distal: variation of the angle  
 587 of the distal limb without modification of the angle of the proximal limb to 4, anti-phase: when the  
 588 angle of one limb varies, the angle of the other limb varies in an opposite way). Procedure extensively  
 589 described by Needham, Naemi, & Chockalingam (2014).  
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592 Figure 2: Mean  $\pm$  SD of SR (left) and IdC (right) values as a function of swimming speed increase in  
 593 both environments (flume in gray, pool in black) and eight swimmers. Linear regressions associated  
 594 with the dynamics of the data are likewise depicted (black lines). (\*) Values significantly higher in  
 595 comparison to the same swimming speed step in the pool. (\*\*) Values significantly lower in  
 596 comparison to the same swimming speed step in the pool.  $p < .05$ .  
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# Constraint impacts on crawl coordination dynamics

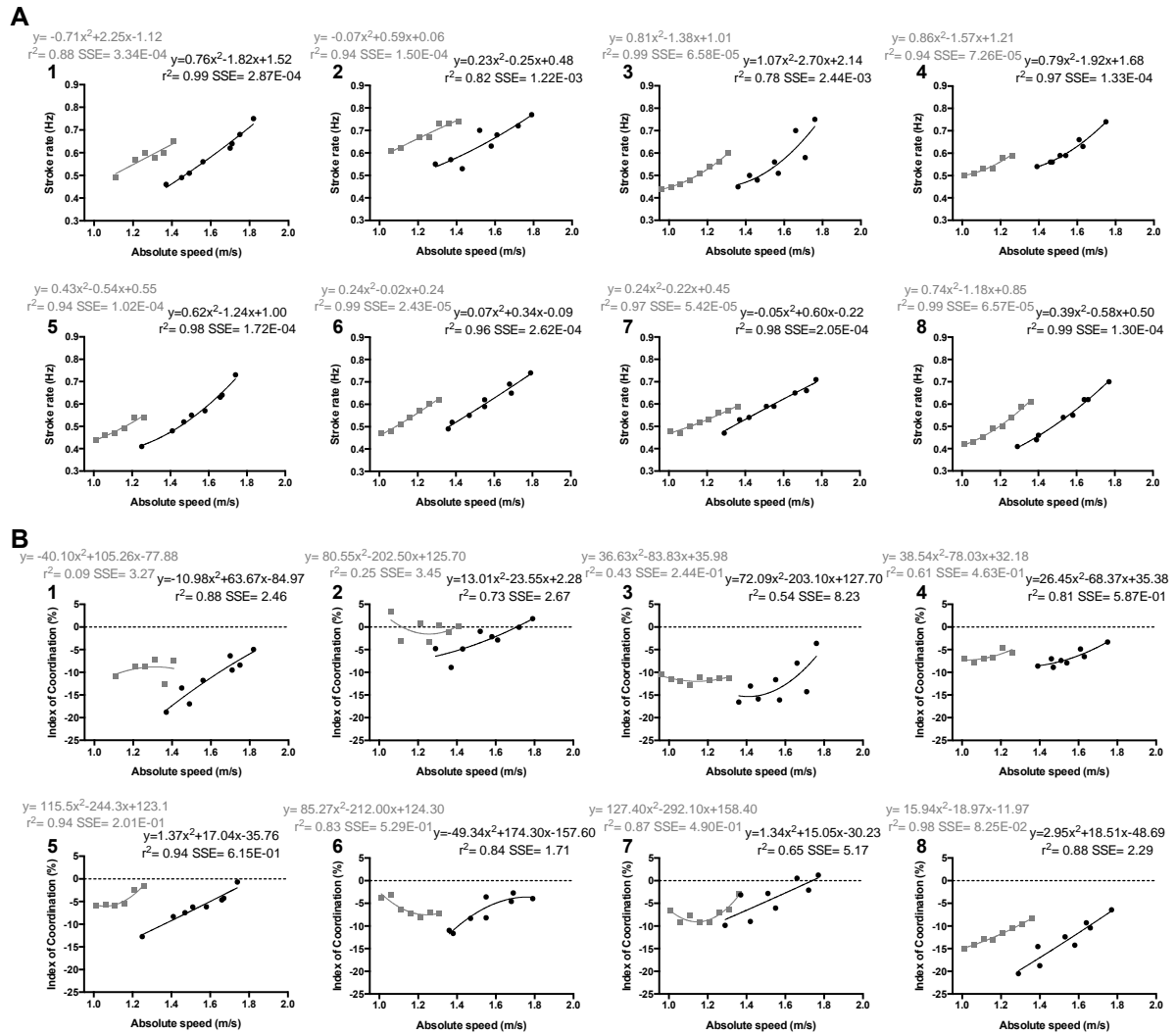


Figure 3: Second-order polynomial models characterizing the dynamics of SR values (A) and IdC values (B) as a function of swimming speed increase for the eight swimmers (graphs numbered from 1 to 8) and for both swimming environments (flume in gray and pool in black).  $r^2$  and SSE (in Hz for SR and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

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