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Submitted on 7 Dec 2023

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Published version

GUIGNARD, B., ROUARD, A., CHOLLET, D., BONIFAZI, M., DALLA VEDOVA, D., HART, John and SEIFERT, L. (2020). Coordination Dynamics of Upper Limbs in Swimming: Effects of Speed and Fluid Flow Manipulation. Research Quarterly for Exercise and Sport, 1-12.

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| 1 | Coordination dynamics of upper limbs in swimming: Effects of speed and fluid | | | | | | |
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| 20 | | | | | | | |
| 21 | Acknowledgments: The authors warmly thank Claudio Gallozzi and Keith Davids, the | | | | | | |
| 22 | medical doctors and the technical personnel of the Sport Science Department of CONI, the | | | | | | |
| 23 | swimming coaches, the swimmers who participated in this study and the Italian Swimming | | | | | | |
| 24 | Federation (Federazione Italiana Nuoto). This project received the support of the | | | | | | |
| 25 | CPER/GRR1880 Logistic, Mobility and Numeric and FEDER XTerM. | | | | | | |
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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 perfored 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.

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

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 comparison to movements performed on dry land (20-25%; [Toussaint, Hollander, van den 51 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 velocity or as a function of swimmer's movements. Therefore, the movements of water 59 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 environments flowing at very slow speeds) present water particles flowing in parallel 62 streamlines, defined as laminar flow. Moving through the fluid or manipulating the flow 63 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 fluid resistance appear as one of the major biomechanical determinants performers have to 67 68 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

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 coordination for sprint speeds (superposition indicated an overlap of the propulsive actions of 84 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).

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

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 ± 3.4 cm, mass: 79.75 ± 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

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.

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 m.s⁻¹ while highest speed was 1.41 m.s⁻¹. Notably, the swimmers globally had to swim above a 150 151 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 45×36×17 mm and was 165 composed of a three-dimensional (3D) accelerometer (\pm 16G), a 3D gyroscope (\pm 1200 °/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).

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

- 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 filter of Madgwick, Harrison, & Vaidyanathan (2011) in the manner of Guignard et al. 178 179 (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%).

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:

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

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

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.

203

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):

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

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.

215

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).

225 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.

230

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).

237

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).

244 Accuracy of models as a function of experimental values

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

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).

251 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_p^2) 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

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.

287 IdC values were strongly impacted by the increase of swimming speed: F(2.49,17.40)=8.80, p=0.001, η_p^2 =0.557. Manipulating the environment led to a strong 288 289 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, $\eta_p^2 = 0.640$. This interaction effect was mainly visible for similar intensities; in particular, IdC 292 293 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

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_p^2 =0.089 and F(1,7)=1.56, *p*=0.251, η_p^2 =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_p^2 =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_p^2 =0.376 and F(1,7)=3.94, *p*=0.088, η_p^2 =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_p^2 =0.849.

310 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. 321

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 highorder variables that define the motor repertoire of expert swimmers. To achieve this objective, we analyzed more than 3010 cycles.

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

327 The increase in swimming speed resulted in a gradual decrease in mean cycle 328 durations for all swimmers in the two swimming environments. For each individual, these 329 dynamics were accurately characterized in the pool and the flume by second-order 330 polynomial modeling of the stroke rate values (no environmental effect on the ordinates at 331 the origin and the directive coefficients of the slope), echoing previous investigations 332 (Bideault et al., 2013; Hay, 2002; Seifert & Chollet, 2009). The coordination variables also 333 presented individual dynamics of the IdC values evolving according to second-order 334 polynomial modeling for the two flow conditions (no significant difference). The present 335 contribution corroborated the results by Bideault et al. (2013) and Seifert and Chollet (2009) 336 obtained in the pool, but brought new insights into the dynamics of the IdC observed in a 337 resistive environment (flume). To face these constraints -potentiated by speed increase-, 338 individuals adapted their coordination. By comparing similar efforts (i.e., no correspondence 339 between absolute swimming speeds in both environments, but similar relative speeds 340 according to the maximal speed achieved in each environment), we observed a progressive 341 increase of the occurrence of the in-phase coordination pattern for lower/upper arm coupling, 342 whereas the occurrence of the three other patterns (anti-phase, distal or proximal) 343 progressively decreased with speed increase in the flume. These dynamics revealed the 344 emergence of a limited dissociation between the two segments in order to cope with the 345 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

the appearance of a range of hand/lower arm coordination patterns that may facilitate thedevelopment 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

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

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 affect the swimmer's buoyancy. These air bubbles trapped in the water, coupled to the size 416 417 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 the range of speeds tested in the present study. Indeed, whether for the low- or high-order 429 430 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 of447 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 may finally observe a possible order effect between the two tested situations. Last, the 466 467 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.

489

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- 570 Tables

| 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 |
| | $\chi^{2}(8) =$ | $\chi^2(8) =$ | $\chi^{2}(8) =$ | | $\chi^{2}(8) =$ | | $\chi^2(8) =$ | | | $\chi^{2}(8) =$ |
| Speed effect | 53.08, | 46.29, | 37.54, | no | 18.07, | no | 41.34, | no | no | 14.38, |
| | p < .05 | p < .05 | p < .05 | | p < .05 | | p < .05 | | | p < .05 |

571 572 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.

573 574 575 *Note*: SD: standard deviation; *: significant difference with flume swimming; χ^2 : Friedman's test. Significant at *p*<.05.

576 577 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 | |
|-----------------------|-------------------------|--|---|---|---|--|
| ц | Speed effect | F(7,7)=7.373, p=0.009, $\eta p^2=0.881$ (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) | |
| ver ar | Environmental effect | N.S. (p=0.998) | N.S. (p=0.891) | N.S. (p=0.302) | N.S. (p=0.125) | |
| Hand/lov | Interactions | F(7,7)=6.740, p=0.011, $\eta p^{2}=0.871$ (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, $\eta_p^2=0.849$ (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, $\eta_p^2=0.860$ (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) | |
| arm/upper arm | Speed effect | F(7,14)=10.757, p=0.000, $\eta_p^2=0.843$ (18.8 ± 2.2% at V1 and 7.5 ± 0.6 % at V8) | F(7,14)=28.958, p=0.000, $\eta_p^2=0.935$ (57.4 ± 5.0% at V1 and 80.3 ± 4.3 % at V8) | F(7,14)=6.598, p=0.001, $\eta_p^2=0.767$ (16.1 ± 1.8% at V1 and 8.6 ± 2.6 % at V8) | F(7,14)=7.064, p=0.001, $\eta_p^2=0.779$ (7.7 ± 1.9% at V1 and 3.6 ± 1.3 % at V8) | |
| ower a | 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) | <i>N.S.</i> (<i>p</i> =0.273) | N.S. (p=0.493) | |

580 Figures



581

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 (y_i) is 584 defined as the angle between the horizontal and the trajectory of the angle-angle plot between i and i 585 + 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). 590



Figure 2: Mean \pm 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.



598 599

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). r² and SSE (in Hz for SR and in % for IdC) values are displayed to assess for the accuracy of the models.