Between exploitation and exploration of motor behaviours: Unpacking the Constraints-Led Approach to foster nonlinear learning in Physical Education

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Highlights for practitioners

This research investigated the effectiveness of a constraints-led approach to pedagogy in Physical Education and how it can foster the exploration of new motor behaviours during learning. Applied in breaststroke swimming, this research highlighted that a constraints-led approach in teaching can actually increase the amount of motor exploration exhibited by learners while leading to an identical performance enhancement. Secondly, results showed that learners exhibited “bad” or irrelevant behaviours during learning, but those who did this exhibited higher retention. Therefore, it could be relevant for the teacher to let the learners practice while exhibiting those behaviours at first sight inefficient, as such a behaviours could reflect an actual exploration and could help the learner to discover useful information. Thirdly, it appeared that learning by analogy is an efficient way of promoting and guiding learner’s exploration and adding a supplemental task constraint which would force the exploration does not increase its efficacy.

Abstract

Introduction

The constraints-led approach (CLA) and more generally a complex systems perspective on motor learning emphasizes the role of perceptual-motor exploration during learning in order to ensure the acquisition of a highly individualized, adapted and adaptable movement pattern. Recent studies have shown that human beings have a strong tendency to exploit already stable patterns rather than looking for new potentially more efficient patterns. In order to shape the amount of exploration, we implemented two learning designs based on a CLA where constraints were used to limit the boundaries of the perceptual-motor workspace of the learners. We sought to highlight how practitioners can play with the perceptual motor workspace boundaries in order to *i*) promote the use of exploratory behaviours and *ii*) guide the learner towards task-relevant functional areas.

Method

For the experiment, twenty-four beginners in breaststroke swimming were allocated to three groups of learning: a *control group* receiving only the goal of the learning, an *analogy group* receiving the goal of learning accompanied by an analogy about "how to perform", a *pacer group* receiving information on the goal of learning and the use of a metronome to continuously push them to "perform better". Based on their assigned group, each learner then followed a learning protocol of 16 sessions with a 10*25m swimming distance per session with the goal of increasing the stroke length for a fixed swimming speed. Both performance (i.e., stroke length) and motor behaviour (i.e., arm-leg coordination) were collected for each session. The arm-leg coordination patterns were computed by the continuous relative phase between knee and elbow angles. Thereafter, a cluster analysis was performed on the coordination in order to get a qualitative label for every cycle performed during the entire process of learning. Based on the use of cluster analysis, an exploration/exploitation ratio was calculated and the increase in performance was determined based on the increase in stroke length.

Results and Discussion

With reference to the exploration/exploitation ratio, our results showed that additional temporary constraints led learners to increase both the nature of their exploration and also the quantity of their exploration. In the meantime, the three groups showed an equivalent final performance enhancement. The aim of manipulating the constraints was not only to push the learner out of his comfort zone, but also to provide relevant information about "where" to explore during learning. For this purpose, the use of analogy appeared as the most relevant constraint to encourage the emergence of efficient behaviour. Interestingly the impact of the analogy was modified by adding the metronome, showing an interaction effect of both constraints. The group using the metronome exhibited different behaviours as compared to the analogy group and showed an increase in exploration during learning compared to the control group. However, although the metronome constantly pushed the learner to improve performance, it did not actually lead to a better improvement of performance when compared to the analogy group. The simple assumption that the constraints forced the learner to explore therefore does not seem a mandatory condition to promote an exploratory learning. Rather, the qualitative nature of the constraint seems the most relevant characteristic that can be manipulated to promote an exploratory learning by *guiding* the learner within the perceptual motor workspace.

Keywords: nonlinear pedagogy, motor exploration, informational constraint, analogy learning, swimming.

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Introduction

This paper aims to investigate the relationship between pedagogical settings in Physical Education (PE) and the promotion of motor exploration during learning. The constraints-led approach (Davids, Button, and Bennett 2008) and more generally a complex systems perspective on motor learning emphasizes the role of perceptual-motor exploration during learning in order to ensure the acquisition of a highly individualized, adapted and adaptable movement pattern. In line with this idea, Gel'fand and Tsetlin (1962) originally proposed the changes in behaviour as a search for the solution of a given problem - this problem being defined as a *degrees of freedom problem* by Bernstein (1967). This proposition is in direct opposition to assumptions about learning that purports it to be an explicit and linear process of internalizing knowledge (see Light [2008] for further discussion). Typically, knowledge is conceived as a pre-existing resource held by the teacher and learning as a process of transferring this knowledge to the mind of the learner. In PE, this linear perspective is exemplified by the existence of fundamental skills or technique that are usually considered as necessary prerequisites for practicing real games or sport (Light 2008).

Conversely, from a *Complex Learning Theory* perspective (Light 2008), learning is neither a linear nor an easily quantifiable process. A major feature of motor learning is non-linearity associated with a functional role of movement variability in enhancing skill acquisition. Noise (i.e., random movement variability) amplifies the exploratory activity and may guide the learner through a perceptual-motor workspace to discover individualized functional solutions to a specific task goal (see Chow [2013] for further explanations). This perceptual-motor workspace is defined as the dynamic landscape from which movement emerges based on the intrinsic behaviour and the constraints at that time (Thelen 1995). It is defined, for example, by the genetic code, developmental level, past experiences, social influences, etc., and is thus continuously shaped by perceptions, intentions, surrounding information, and physical constraints (Thelen and Smith 1994). Navigating through the perceptual-motor workspace allows the learner to explore new motor solutions while being somewhat limited by the constraints, which reduces the set of potentials (Newell 1991). During these repetitions, the learner's intrinsic behaviour will be changed through the stabilization of the new areas explored. Motor *exploration* in this context refers to the actual use of a different motor solutions (but still available in the workspace) to reach an identical task goal, and can be assessed through movement variability (Stafford et al.

2012). Conversely, *exploitation* of a coordination is reflected by the repetition or recurrence of an identical pattern over a more or less long period, allowing for a certain stabilization of the considered coordination. To date, it is more a prediction from learning theory that greater exploration is associated with improved performance rather than a strong experimental result. However, exploration is supposed to play an important role in enabling the learner to discover the optimal coordination pattern or patterns for a task, as well as the parameters that make for a flexible and efficient movement solution. The workspace evolves qualitatively with on-going practice because even the temporary stabilization of new explored movements allows further exploration to continue (Sporns and Edelman 1993). In the early stages, the goal of learning is therefore to find the optimal workspace region, which corresponds to the movement pattern that best satisfies the task, environmental, and organismic constraints. Learning is seeking, exploring, discovering, assembling, and stabilizing functional movements (Newell 1986; Williams, Davids, and Williams 1999). This definition of learning through motor exploration highlights the final product of learning as the stabilisation by expert performer of a highly individualized and adaptable movement solution.

The individualized feature of expert movement solutions has been evidenced in many activities. For instance, in a very recent experiment investigating the "pursuit of, let's say, the perfect basketball free throw", Hagen and Valero-Cuevas (2017, 3) specifically focused on movement analysis in a "technique intensive" activity (i.e., where technique is considered as a key factor of performance, Light and Kentel, 2015); The basketball free throw. The authors demonstrated how throws that exhibited initial and final conditions of success showed both different movement trajectories and different muscle contraction velocities. They concluded that valid trajectories are not intrinsically equivalent and therefore each possible movement solution seems evaluated via a user-specified cost function [e.g., energy cost (Dingwell, John, and Cusumano 2010), jerk (Flash and Hogan 1985)]. In other words, across activity, expertise is not reflected in the acquisition of a specific movement solution but rather a very unique, individually-adapted, efficient solution.

Paradoxically, whilst exploration has been positioned as functional for learning, in many instances researchers have shown that stable behaviours will be strong attractors, *i.e.,* that human beings have a strong tendency to exploit already stable patterns rather than looking for new ones which can be even potentially more efficient (Neal, Wood, and Quinn 2006). When practicing a new task, a learner may present initial tendencies pushing the individual to act in a specific way and those initial tendencies might limit the perception of the whole potential offers by the task (Pacheco, Hsieh, and Newell 2017). Lee, Farshchiansadegh and Ranganathan (2017) also recently showed that this phenomenon of limited exploration was amplified with children compared to adult learners even when the task was designed to minimize biomechanical constraints for children. To account for such phenomenon, the Constraint-led Approach (Davids, Button, and Bennett 2008) emphasizes that constraints influence performers by temporarily limiting their range of possibilities. For learning tasks, the temporary use of constraints could thus be used to promote and guide exploration. Actually, constraints do not influence the learning process independently, but rather through their interaction, which shapes the perceptual-motor workspace of each learner and focuses their exploration during the acquisition process (Chow et al. 2011). Modifying the constraints could be used to guide the exploration of the perceptual-motor workspace while still retaining the key variables of the information-movement coupling that regulates behaviour. From this perspective, the role of a pedagogical setting refers to pushing the learner out of his/her comfort zone and to guide him/her towards task-relevant areas.

The aim of this paper was therefore to investigate the effectiveness of informational constraints to foster exploratory behaviours during practice in PE. More specifically, we sought to highlight how practitioners can shape the perceptual motor workspace in order to *i*) promote the optimal use of exploratory behaviours and *ii*) guide the learner towards task-relevant functional areas.

Methods

Participants and learning design

Twenty-four students, all novices in breaststroke swimming, voluntarily participated in this study. Each participant signed an informed consent form after receiving oral and written descriptions of the procedure, which was approved by the university ethics committee. Two swimming instructors selected the 24 individuals from a pool of approximately 200 swimmers who performed a 50 m breaststroke swim at a comfortable speed. The two exclusion criteria were principally related to the validity of their initial breaststroke technique. Importantly, they had to be able to (a) perform a symmetrical leg kick and (b) perform leg and arm movements at the same frequency. The swimming instructors characterized the swimmers as being in the first stage of learning (i.e., coordination stage), during which learners still have to establish the basic relationships among the key components of the behaviour (Newell 1986). Specifically, from Newell's perspective, a coordination pattern can be seen as a function that organizes the initially independent elements of a system into a functional unit in time and space (1986). The main characteristics of swimmers at this stage are a lack of glide between cycles, mainly because of uniform motions (i.e., no limb acceleration during propulsion and no glide time), and a superposition of contradictory actions (e.g., leg propulsion during arm recovery; Komar et al. 2014; Seifert et al. 2011). Participants (who were all males), were separated into three groups of eight participants each (mean age = 19.2 years, SD = 0.9). The first group was called 'control' and received only the goal of learning without any information on how to perform, the second group was called 'analogy' and received an additional information on how to perform through the use of an analogy, and the third group was called 'pacer' as they received an additional information on how to perform and included the use of a metronome to continuously push them to "perform better" by constantly decreasing the frequency of the metronome.

All participants participated in 16 learning sessions with three test sessions (pre-, post-, and retention test). The entire program lasted 9 weeks, with two sessions per week. All participants performed at a different time during the day/week, in order to avoid any interaction between participants or groups during the protocol. During each session, in a 25 m indoor pool, participants had to complete 10 x 25 m at sub-maximal speeds (70% of their maximal personal speed). This sub-maximal speed, based on the maximal speed performed by each participant during the first session, corresponded to the working speed during all the learning process (i.e., the speed was constant during all the learning process). Each test session consisted 4 x 25 m in free condition where learners were asked to "perform as best as possible" (i.e., with maximal amplitude). Each learning session consisted of 2 x 25 m in free condition where learners were asked to "perform as best as possible", followed by 8 x 25 m where the learners were asked to follow the specific instructions assigned to their group. Each session lasted approximatively 35 min per participant and included a 10 min of warm-up followed by the 10 trials with a start every 2 min 30 sec (a trial lasted 30 sec followed by a 2 min rest period). The retention test was performed two months after the post-test. Participants were asked to avoid practicing the breaststroke during the entire experiment (from pre-test to retention test), except during the experimental sessions.

General goal of learning and specific instructions

For all the participants, the general goal of learning was to increase the stroke length (i.e., distance achieved per cycle, in m.cycle^{-1}) while maintaining the same sub-maximal speed. In the French physical education curriculum, the increase of stroke length in learning swimming is considered as a relevant qualitative indicator of swimming competency and therefore represents a widely used indicator for assessment. Learners were informed of this general goal at the beginning of each session. The basic rules of breaststroke swimming were provided to the participants (as a reminder) during the first session, and only if necessary thereafter. If learners failed to follow the rules or the targeted speed, they were stopped by the experimenter and had to perform the trial again. After each trial, learners were informed of their mean stroke length values. No other information was given to the learners from the control group during the 16 sessions.

In this control group, the objective was to avoid constraining the range of possibilities more than the free practice. Thus, this group was considered as the less constrained during exploration. For the two other groups, the general goal of the learning task was also to increase the stroke length. In addition, it included an additional temporary informational constraint that focused on the movement form. Specifically, the analogy group received an instruction through an informational constraint focusing on movement form: “glide two seconds with your arms outstretched”. This analogy was a “verbal representation of the task (...) relying very little on explicit verbal instructions or action rules”. Instead of providing a set of verbal instructions on movement form during each phase of the swimming cycle (e.g., Wulf, Lauterbach, and Toole 1999, 122), the presented instruction was essentially directed towards the specific glide position of the arms, which focused on movement form. This instruction was unique and did not cover all the successive phases of the breaststroke cycle (i.e., leg propulsion, glide, arm propulsion, recovery). The pacer group also received this instruction about movement form but in addition, had to follow a decreasing frequency of a metronome (Aquapacer, Challenge and Response, Inverurie, UK) (Thompson et al. 2002). More precisely, learners were asked “to glide with their arms outstretched when they hear a sound from the metronome and to perform only one cycle between two successive sounds”. The frequency of the metronome was decreased by seven percent every two sessions (based on the average decrease observed on the control group), which represented a decrease of two or three points per level (in cycles per minute). The stroke frequency at the beginning of the learning process was the one freely expressed by participants during the pre-test.

The amount of decrease was based on the decreased in stroke frequency exhibited by the other groups (i.e., control and analogy), but if the learner in the pacer group exhibited a stroke frequency lower than his targeted frequency during his free practice, this targeted frequency was decreased and the next level was adjusted. As for the 'analogy' group, no precise information about movement form was given to the learner, but in this condition, the increase in stroke length was required. Therefore, the pacer condition was considered as more constraining than the analogy condition because in addition to an instruction, the metronome matching task forced the learner to move outside of his comfort zone.

Data collection

Participants were equipped with inertial sensors including 3-D accelerometers, 3-D magnetometers and 3-D gyroscopes (MotionPod3, Movea, Grenoble, France) (Seifert et al. 2014). The acquisition frequency was 100 Hz. Four motion sensors were positioned on the left side of the swimmers, respectively on the forearm (posterior surface of the proximal portion), the arm (posterior surface of the distal portion), the thigh (anterior surface of the distal portion), and the leg (anterior surface of the proximal portion), in order to have the sensors in direct contact with a bony part of the limb. At the beginning of each session, the position of the motion sensors was placed on a black marker, which defined the location of the sensor from the last session. Swimsuit was also worn on the two limbs where sensors were placed in order to limit resistances due to the presence of the sensors. Once the swimmer was 'suit-up', he entered the second lane in the pool (i.e., at least two meters far from the wall to avoid any magnetic disturbance), and performed the 10 repetitions. Once the trials were completed, the data were uploaded and synchronized a posteriori with Matlab r2012b. Thereafter, elbow and knee angles were computed for each trial by calculating the relative angle between two sensors. Time series representing knee and elbow angles were then computed. These time series were filtered with a low-pass Fourier filter (cut-off frequency 8 Hz) and partitioned cycle per cycle (i.e., one cycle beginning with a maximal knee flexion and finishing with the next maximal knee flexion). The first two cycles as well as the last two cycles were removed in to account for acceleration or deceleration effect. For each trial, knee and elbow angular positions for 3 to 17 cycles were kept to characterize the coordination of the swimmer.

Processing of Performance Data

During each trial, the instantaneous stroke frequency (f, in Hz) was assessed for each cycle from the duration of each cycle (measured with the motion sensors) following the equation $f = 1 / cycle\ duration$ (in seconds). Therefore, changes in performance were actually defined by the decrease in stroke frequency (i.e., the assessment of the decrease in stroke frequency was considered equivalent to the assessment of an increase in stroke length as the swimming speed was constant) between the pre-test and post-test, and between the post-test and the retention-test.

Processing of Behavioural Data

First, for each cycle performed by the learners during the entire learning process, the nature of the behaviour was derived from the arm-leg coordination and was assessed by the Continuous Relative Phase (CRP) between knee and elbow angles. The CRP was computed based on elbow and knee angles in the same way as previous experiments (Seifert et al. 2011), which was considered as an effective parameter to quantify the nature of swimmer's behaviour. The first CRP value of the cycle defines the capability of the swimmers to synchronise knee flexion with arm extension. A value close to -180° (i.e., anti-phase relationship) indicates that the elbows are at their maximal extension when the legs are at their maximal flexion (prior to initiating an extension). A value closer to 0° (i.e., in-phase relationship) indicates that the elbows are maximally flexed when the knees are at their maximal flexion. This in-phase coordination indicates an identical motion of both arms and legs (i.e., flexion of both pairs of limbs or extension of both pairs of limbs). Therefore, it indicates how the swimmer superposed contradictory actions (i.e., leg propulsion during arm recovery or leg recovery during arm propulsion) (see Seifert et al. [2011] for further explanations).

Second, a cluster analysis procedure was used in order to differentiate the patterns of coordination exhibited by learners (Rein et al. 2010). One time series of CRP per cycle from the entire experiment (i.e., all the cycles, all the trials, all the participants, all the sessions and all the groups) were used to compute the cluster analysis. Such a cluster analysis allows partitioning the entire set of cycles into meaningful sub-groups or clusters, whereas the "real" number of groups is unknown a priori. The Fisher-EM algorithm has been used for the present experiment (Bouveyron and Brunet 2012). The Fisher-EM algorithm is an iterative cluster algorithm that projects the data in a new subspace at each iteration in such way that emerging clusters maximize the Fisher information (i.e., maximize the inter-cluster distance while minimizing the intra-cluster distance).

Third, the time series of exhibited coordination were re-constructed putting one cycle after the previous one in the chronological order they were performed, representing the successive behaviours that were exhibited by a learner (Figure 1 for an example). When a similar behaviour was repeated between two successive cycles, we identified it as *exploitation*, whereas the succession of different behaviours between two successive cycles was defined as *exploration*. The exploration/exploitation ratio was then calculated as the number of occurrence of *exploration* divided by the number of occurrences of e*xploitation*. A high exploration/exploitation ratio (E/E ratio) refers to a situation where a participant explores a lot and conversely, whereas a ratio equal to 1 indicates an identical amount with reference to exploration and exploitation. This E/E ratio provides information about the global quality of an instruction to encourage the participants to leave their initial behaviour in order to explore new patterns of coordination.

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Statistical Analysis

With reference to the analysis of the performance indicator, after normality and homogeneity of variance were checked, a two-way mixed model ANOVA [between-subjects factor: Group x within-subjects factor: Time of testing] was used to compare the stroke frequency values between groups and between the time of testing. When necessary, the p values were corrected for possible deviation from sphericity using the Greenhouse-Gesser correction when the mean epsilon was lower than 0.75. Otherwise, the Hyun-Feld procedure was used. Partial eta squared (η_P^2) was calculated as an indicator of effect size, considering that $\eta_P^2 = 0.02$ represents a small effect, $\eta_P^2 = 0.13$ represents a medium effect and $\eta_P^2 = 0.26$ represents a large effect (Cohen, 1988). When normality and/or homogeneity of variance was not reached, a Kruskall-Wallis test for independent samples was used to estimate the differences between groups of practice and in the case of any significant difference, Mann-Whitney tests for independent samples were computed for pair-wise comparisons.

Results

Performance outcome

Out of the 24 participants involved in this study, 4 were not able to follow the entire experiment and were therefore excluded. The two-way ANOVA showed a significant interaction effect on the stroke frequency between group and time of testing, $F(3.734, 741.26) = 34.72$, $p < .001$, $\eta p^2 = .149$ (with a Mauchly $W = 0.919$ and $\varepsilon = .925$). Bonferroni post-hoc tests thereafter showed that all three groups decreased their stroke frequency after practice in the same way (i.e., no differences between group during the pre-test as well as during the post-test, all $p_s > .573$). However, when no difference appeared between post-test and retention test for the *analogy* and the *pacer* group, a slight but significant increase in stroke frequency appeared for the control group ($p < .001$), highlighting a lack of retention of learning for this group (Figure 2).

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Coordination Profiling

The output of the cluster analysis showed the emergence of 11 different arm-leg coordination patterns throughout all the learning phase (i.e., during the 2.5 months) (Figure 3). The BIC criterion ([2-16] potential clusters) showed that the optimal number of clusters that best fitted the data was 11. Indeed, 11 clusters corresponded to the first value of the plateau* in the BIC vector [BIC = -12266770; -12054679; -11835712; -11758107; -11478308; -11414261; -11299105; -11096673; -10771125; -10382736*; -10477354; -10527102; -10513261; -10358955; -10398427].

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Table 1 shows the number of different patterns exhibited by each individual: the number of visited patterns represents the number of patterns exhibited at least once whereas the number of stabilized patterns represents the number of different patterns repeated over at least one full trial in a continuous fashion (i.e., over one full 25-m swim). A Kruskall-Wallis test for independent samples showed that the number of explored patterns did not differ significantly between the groups ($p = 0.334$) but the number of stabilized patterns was significantly different between groups ($p = 0.047$). Thereafter, Mann-Whitney tests showed that the number of stabilized patterns was higher for the control group regarding the pacer group ($p = 0.038$) and higher for the control group regarding the analogy group ($p = 0.038$) whereas the control and the analogy group did not show any difference ($p = 0.902$).

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Exploration/Exploitation Ratio

With reference to the exploration/exploitation ratio (Table 2), a Kruskall-Wallis test for independent samples showed significant differences between groups ($p = 0.006$). Pair-wise comparisons using Mann-Whitney test thereafter showed that the control group exhibited a lower ratio than the analogy group ($p = 0.002$) and the pacer group ($p = 0.035$).

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Discussion

Effect of additional constraint on exploration

Broadly speaking, the different constraints used in this experiment showed an effect on the predominance of certain patterns of coordination compared to the control group. Despite different behaviours exhibited, the final performance of all 3 groups were not significantly different as they all decreased their stroke rate the same way after practice. More precisely while the control group showed predominantly the patterns 2, 4, and 6, the use of an analogy limits the appearances of these patterns 2, 4, and 6 to preferred patterns 1, 3, 7, 8, and 9. The pacer group showed more cycles associated with the pattern 10, and less associated with patterns 1, 2, 3, 4, 5, and 6. Interestingly, patterns 2, 4, and 6 were principally exhibited during the beginning of the learning process, and the fact that the informational constraints limited their occurrence may reveal the ability of these additional constraints to favour exploration of new patterns (i.e., to favour an early departure from the initial behaviour). As Newell (1986) suggested, the acquisition of a new coordination is the result of a process aiming to manage interacting constraints acting on learners during practice; modifying constraints can lead to different emerging coordination.

Whatever the nature of the additional constraint, learners showed during the free trials (i.e., trials 1 and 2 of every session) an exploration/exploitation ratio lower than during the constrained trials (i.e., trials 3-10 of every sessions). This result showed that within a session, the constraints were able to place learners into an explorative activity more so than during their free practice (Davids, Button, and Bennett 2008; Renshaw, Chow, Davids, and Hammond, 2010).

In fact, the addition of a temporary constraint (i.e., the analogy or metronome) during the practice did not increase the global number of visited patterns during the entire practice period between the control and the constrained groups, but rather limited the number of stabilized patterns of the constrained group. This result suggests that such a constraints-led approach can “keep open” the range of possibilities of the learner while orienting him towards specific new patterns and more importantly, preventing total instability of those newly acquired patterns. This possibility to stabilize some patterns during the learning process is of paramount interest in our case as a stabilized pattern could serve as a bridgehead for exploration, like periods of rest during a *costly exploration*. Learning would therefore be predicated as a non-linear process, with longer or shorter periods of back-and-forth between newly explored behaviours and previously stabilized behaviours (Teulier and Delignières 2007). Therefore, if learning can benefit from back-and-forth, teachers should accept momentary degradations in student behaviours and/or performances during practice because those behaviours can favour later improvements. By extension, the principle of continuous assessment might be revisited, as some periods of non-assessment should be included in PE curriculum, when students can practice without being under teacher’s supervision/evaluation. Those periods could help learners to freely explore new (and only potentially more relevant) motor solutions, even if those new solutions imply a momentary decrease in performance.

The slight but significant increase in stroke rate during the retention test of the control group could support the relevance of exploration during learning in order to increase the retention of learning. Although the simple fact that the two experimental groups received an information could merely explain this lack of retention for the control group, the transient stabilisation (i.e., the periods of exploitation) occurring between successive periods of high exploration for the experimental groups could also be an alternative explanation, therefore advocating for the existence of an optimal balance between exploration and exploitation.

Analogy versus Pacer as a temporary constraint

In terms of quantity of exploration, the analogy group appeared as constraining as the pacer group in the way they promoted exploration. The analogy group did not show an exploration/exploitation ratio lower than the pacer group. This result was not really expected as the pacer constraint was assumed to elicit the most exploration by requiring adaptation to the pacer on a stroke by stroke basis. Indeed, while it was easily possible for the swimmers from the analogy group not to strictly follow the instruction during every cycle, the ones from the pacer group were constrained continuously by the metronome, cycle after cycle. In that sense, the fact that the metronome really "imposed" an exploration (or at least a change in behaviour in order to attempt to follow the task rules) did not appear as a necessary condition to actually promote the exploration. In contrast, a single informational constraint seemed sufficient to encourage exploration. This result advocates for the benefit of motor exploration where the emphasis is to "*focus learning rather than forcing learning*" (Storey and Butler, 2013, p. 133). However, this pacer constraint generated qualitative reorganizations that differed from the control and from the analogy practice conditions, which was in line with previous use of a metronome in movement learning (Ford, Wagenaar, and Newell 2007). The synchronization of the upper limbs to an external metronome has already been used in the rehabilitation of stroke patients in learning to walk (Ford, Wagenaar, and Newell 2007). Orienting auditory signals towards the arms showed an effect on the entire motor organization of the walking pattern (i.e., including effect on the amplitude of rotation of the hip). In this study, without precisely prescribing the movement form, the focus of the learner's attention to an outstretched position of the arms was supposed to lead learners to reach and stay in this (hydrodynamic) position while waiting for the signal of the pacer. Interestingly the impact of the instruction was modified by adding the metronome and there was an interaction effect of both constraints (i.e., interaction between informational constraint and the presence of the metronome). Teaching is therefore not a question of adding gradually some information into the learning environment, but rather a question of designing an effective constraint-led learning environment that leads to the emergence of effective exploration of the workspace.

In terms of the nature of the specific patterns demonstrated, an interesting point to highlight is the potential irrelevant exploration exhibited by the pacer group. Indeed, the pattern represented by cluster 10 (Figure 4) represents a highly irrelevant behaviour in breaststroke swimming as it relies on a long period of the cycle spent with the arms flexed (see Komar et al.

[2014] for specifications on the effectiveness of breaststroke coordination). In the meantime, this behaviour was preferred by the pacer group as 66.23% of its total occurrences were observed in this group (9.95% for the analogy group and 23.82% for the control group). Despite the appearance of those irrelevant behaviours, the increase in the final performance was the same for both groups, suggesting a potential long term relevance of those momentarily irrelevant behaviours. In other words, students potentially learn from those irrelevant behaviours and it might be relevant for the teacher to let them practice while exhibiting a so called "bad" behaviour, as this behaviour could correspond to an actual exploration and could help the learner to discover useful information. For instance in the present case, this behaviour (cluster movement 10) consisting of a "glide" time with the arms flexed could be a very relevant (even momentarily) behaviour to help swimmers to be aware of the hydrodynamics of their body where they will experience high drag. The absence of a decrement in performance of this pacer group at the end of the learning might be evidence of the presence of some "relevance of those irrelevant behaviours". The qualitative nature of learning therefore would be non-linear, in the sense that reaching a new and more effective behaviour might require the learner to regress and use less effective behaviours. In other words, learning is not reflected by a linear increase in the quality of the behaviour (Chow 2013).

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Constraint-led approach to guide the exploration

In summary, additional temporary constraints can lead learners to adopt different patterns of coordination during the exploration, but also to foster the exploratory behaviours. Even if the results of the pacer and analogy groups validate the hypothesis on a constraints-led approach favouring relevant exploration (Davids, Button, and Bennett 2008), results from study also questioned the existence of an optimal ratio between exploration and exploitation during learning. Indeed, the presence of more exploration than exploitation might reflect the absence of a real positive exploration, but rather a high instability of the coordination (Kelso 2012). This instability may be due to a strong competition between the behavioural information and the learner's original behaviour. In other words, is there a maximal amount of exploration that should not be exceeded to stay effective? Conversely, does exploration really need those bridgeheads and how much? In other words, is the exploitation necessary so that the learner can actually and deeply explore (at a different level) the solution space around a stable coordination pattern to become more attuned to information (e.g., by adapting movement amplitude or movement frequency)? Also, the actual benefit of the exploration process during learning in terms of final performance must be revealed, whether in terms of transfer of learning to other swimming techniques or in terms of adaptation of the breaststroke coordination to increased swimming speed or to cope with a perturbation.

In fact, those results confirm a recent publication (Hossner, Käch, and Enz 2016) suggesting that there is an optimal degree of fluctuations and most importantly a strong qualitative nature of the exploration. In other words, the aim of manipulating the constraints is not only to push the learner out of his comfort zone, but also to provide him relevant information about "where" to explore during learning. The question for practitioners when using CLA is how to shape the perceptual-motor workspace in order to guide learners to a relevant area. Pacheco et al. (2017) mentioned this information as the *convergence information*; specifically, a perceivable relation that guides the individual to the "most useful information" in the task space. From a practical point of view, our results corroborate that an informational constraint with a focus on the movement form seemed relevant in helping beginners to explore new motor solutions (Komar, Chow, et al. 2014), and thus could be considered as an example of such a "convergence information".

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Tables & Figure caption

Table 1. Number of different behaviours visited during the 17 sessions (left) and among them the number of different behaviours that were stabilized during at least one trial.

Table 2. Exploration/exploitation ratio for each learner for the three learning conditions ([1] significantly different than the control group)

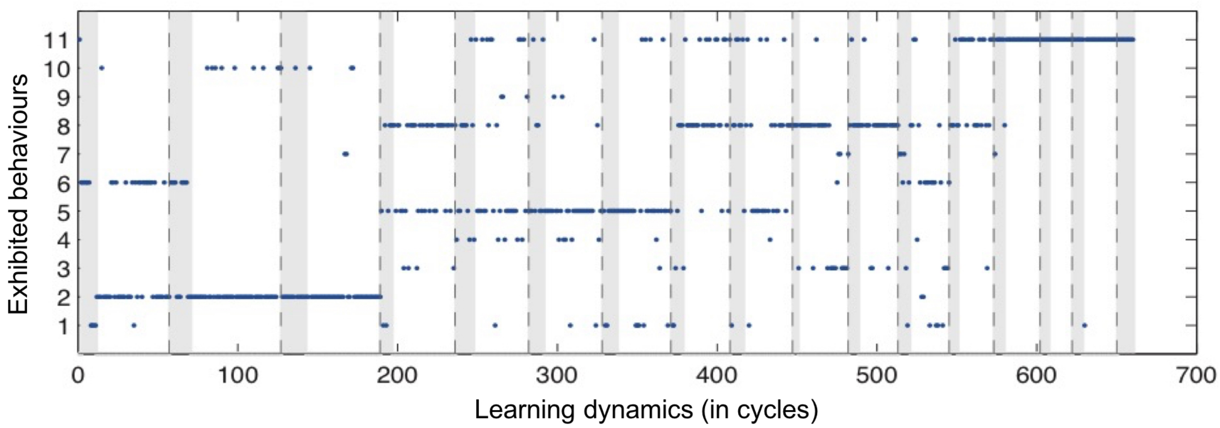

Figure 1. Example of the dynamics of learning for a single learner from the analogy group (one point representing one performed cycle) from the first cycle performed on the first session (left) to the last cycle performed on the last session (right).

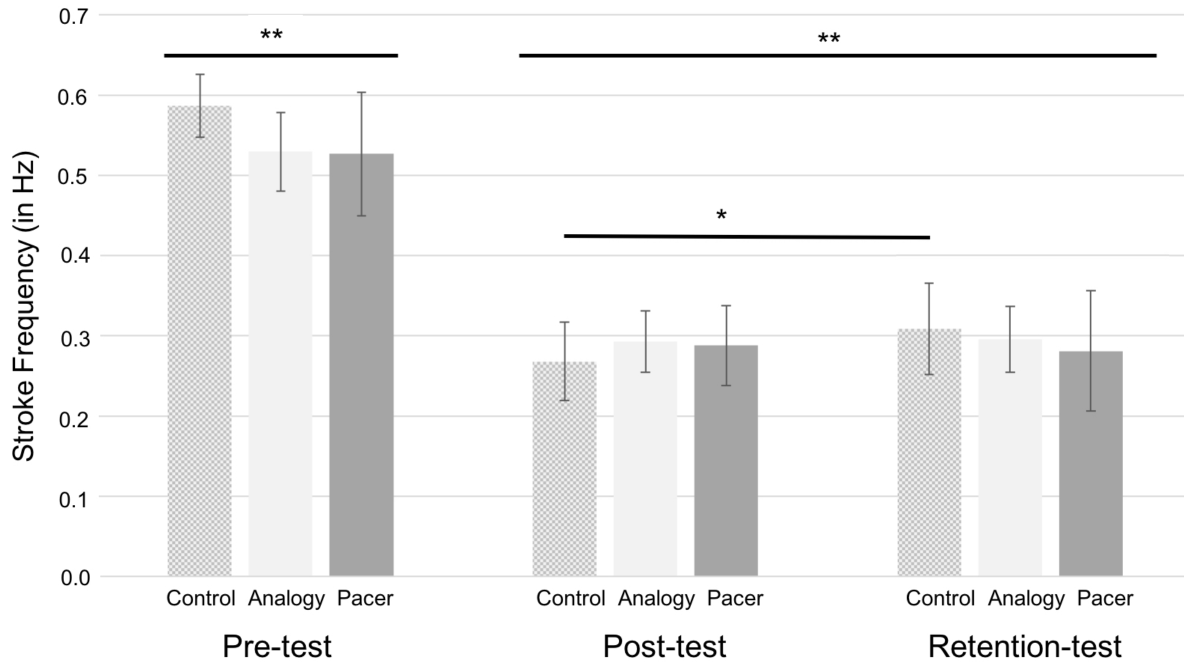

Figure 2. Average stroke frequency per time of testing (pre/post/retention tests) exhibited by swimmers in function of group of practice (* significant increase from post-test to retention-test for the control group; ** significant decrease from pre-test to post- and retention-tests for all groups).

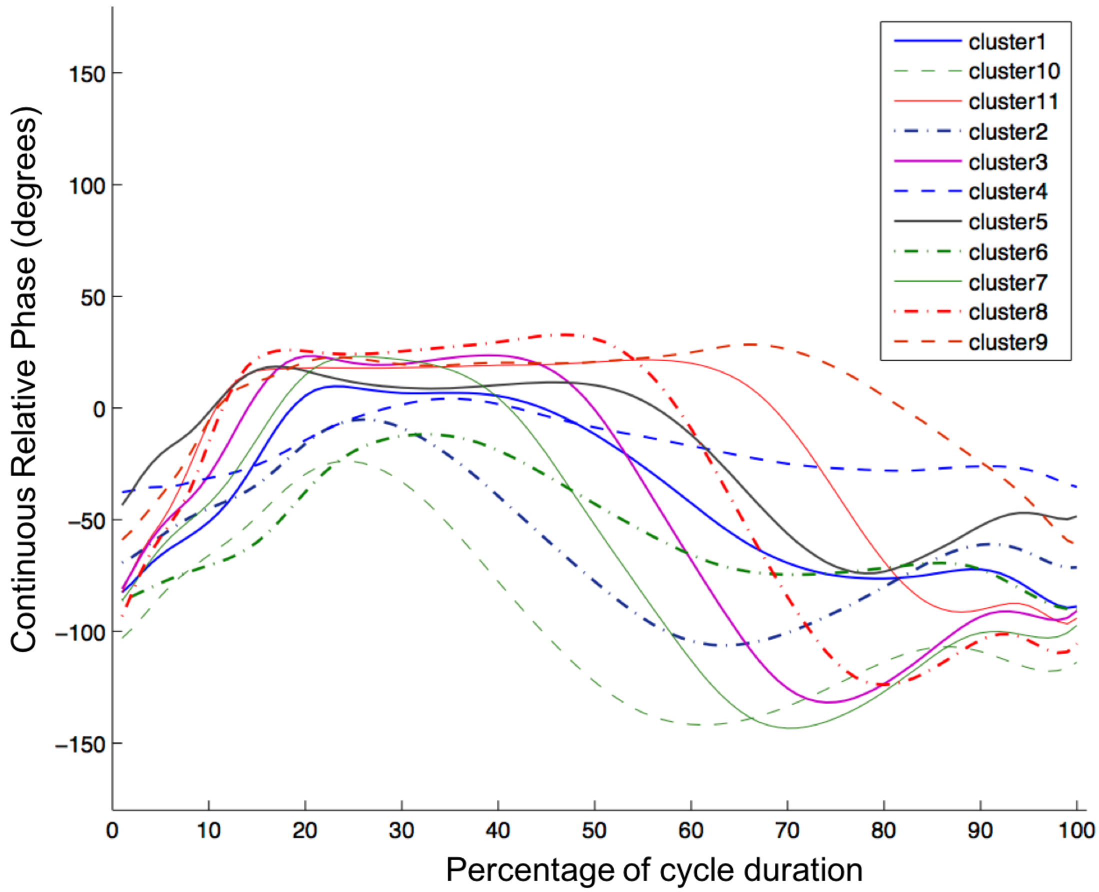

Figure 3. Mean patterns of coordination for each emerging cluster from cluster 1 to cluster 11.

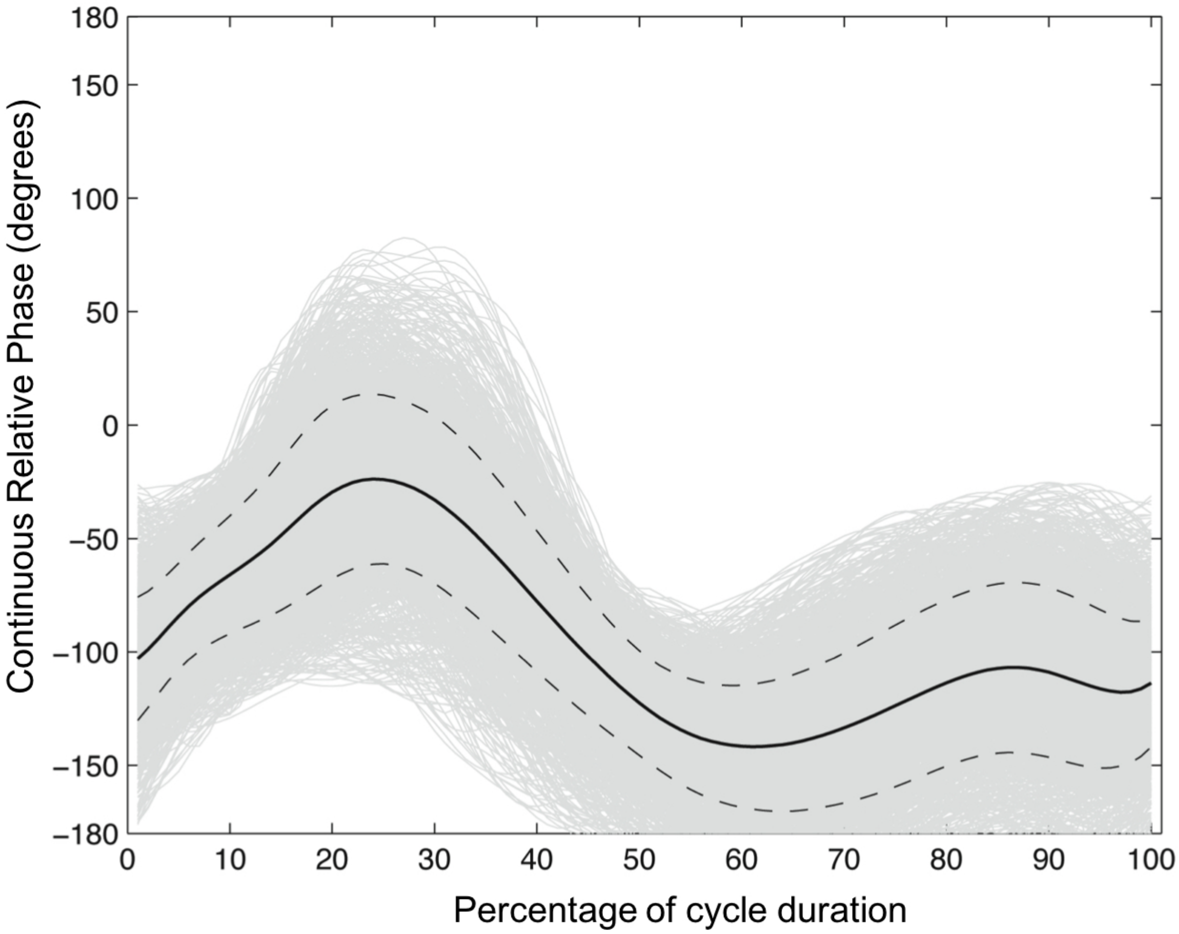

Figure 4. Mean pattern (black line) of coordination for the cluster 10 (standard deviation in dotted line, individual patterns in grey).