RADICAL EMBODIED COGNITIVE SCIENCE OF HUMAN BEHAVIOR: SKILL ACQUISITION, EXPERTISE AND TALENT DEVELOPMENT

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RADICAL EMBODIED COGNITIVE SCIENCE OF HUMAN BEHAVIOR: SKILL ACQUISITION, EXPERTISE AND TALENT DEVELOPMENT

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EDITORIAL
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Editorial: Radical Embodied Cognitive Science of Human Behavior: Skill Acquisition, Expertise and Talent Development

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Editorial on the Research Topic

Radical Embodied Cognitive Science of Human Behavior: Skill Acquisition, Expertise and Talent Development

In this Research Topic, we aim to examine how radical embodied cognitive science (RECS), as a theoretical approach emphasizing the relationship between the body and the environment or ecosystem, may inform conceptions and analyses in the field of movement coordination and skill acquisition and provoke thinking about the full range of psychosocial processes and activities, including experience, mindset, or social interactions.

While other article collections have sought to elucidate key developments of a general conceptual nature, regarding relationships between different schools of thought captured underneath the broad umbrella of radical embodied perspectives, our focus has been more specific and concrete. We wish to bring together examples of theoretical and empirical research, which illustrate how radical embodied cognitive science casts new light on questions of traditionally "higher" functions or directly challenges traditional conceptualizations of those functions. The RECS is often introduced and discussed through 4E concepts (embodied, embedded, enacted, and extended), with some differences explored within and between aligned frameworks (e.g., enactivism, ecological psychology, dynamical system theory, ecological dynamics, phenomenology, etc.). In our Research Topic, we did not restrict RECS to any specific framework, method, or nature of data, but we were open to research diversity about skill acquisition, expertise, and talent development.

The Research Topic is composed of 13 articles representing various types of manuscripts that cover reports of original research to reviews, perspectives, conceptual, and theoretical articles from 41 researchers working in 12 different countries. It is obvious that a community of RECS researchers is spreading over the world and embracing a growing number of domains of human activity.

Rather than introducing each article individually, we have decided to write this editorial by focusing the mind of the future reader on several conclusions that could be drawn from all of these contributions. To do that, we identified five key points in the articles, and we highlight the most relevant to each of us in turn:

(a) Because of the multi-scale nature of body-environment interactions, multilevel methodology and analysis seem to be needed for a complete examination of the relationship between the performer and environment. Montull et al.'s report of original work examining the experience of flow as an emergent property of the behavioral coupling between the performer and environment in performance of a slackline task provides a concrete illustration of how this change in perspective can offer new productive insights.

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(b) An in-depth examination of the concept of "representative design" is developed by considering the best way to capture the essence of the activity analyzed. This is suggested by Coste et al., explaining how creativity can be explored, and also by the study of Rączaszek-Leonardi et al., which included cultural artifacts involved in the recognition of difficult experiences.

(c) A growing number of works, reflections, or guidelines that focus on education, prevention, learning, or training have emerged connected to the RECS approach. The study of Button et al. on treading water coordination, the pedagogical framework of Otte et al., and the review of van der Kamp et al. provide clear examples of this, illustrating that radical embodied approaches are not an academic matter but bring with them important practical considerations that affect practice designs.

(d) The "phenomenological" route for understanding body-environment interactions provides additional insights to the strict ecological-dynamical behavioral analysis. This is exhibited by Rochat et al.'s investigations of the experience of learning, linked to the behavioral fluency of climbers observed in a novel and unchanged environment, as well as with the study of van Westen et al. on the effect on the clinician's interactive activity with patients with deep brain simulation.

(e) The "crisis" or "limitations" in certain fields of research because of conceptual, methodological, or theoretical issues might be overcome using a radical embodied approach. This is suggested, for example, by Malinin's article about creativity, by Pacheco et al.'s framework outlining a Search Strategies Approach to skill acquisition (SSA), or by Raab and Araújo's exploration of dialogue and the place of representations in RECS.

This special issue is rich, diverse, and provides inspiring methods and models that RECS principles bring forth. We are sure that attentive readers will find new opportunities to enrich their own research and professional activity and may uncover a new world of acting in research and practice.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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CONCEPTUAL ANALYSIS
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Embodied Cognition With and Without Mental Representations: The Case of Embodied Choices in Sports

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In this conceptual analysis contribution to the special issue on radical embodied cognition, we discuss how embodied cognition can exist with and without representations. We explore this concept through the lens of judgment and decision-making in sports (JDMS). Embodied cognition has featured in many investigations of human behavior, but no single approach has emerged. Indeed, the very definitions of the concepts "embodiment" and "cognition" lack consensus, and consequently the degree of "radicalism" is not universally defined, either. In this paper, we address JDMS not from a rigid theoretical perspective but from two embodied cognition approaches: one that assumes there is mediation between the athlete and the environment through mental representation, and another that assumes direct contact between the athlete and the environment and thus no need for mental representation. Importantly, our aim was not to arrive at a theoretical consensus or set up a competition between approaches but rather to provide a legitimate scientific discussion about how to explain empirical results in JDMS from contrasting perspectives within embodied cognition. For this, we first outline the definitions and constructs of embodied cognition in JDMS. Second, we detail the theory underlying the mental representation and direct contact approaches. Third, we comment on two published research papers on JDMS, one selected by each of us: (1) Correia et al. (2012) and (2) Pizzera (2012). Fourth, following the interpretation of the empirical findings of these papers, we present a discussion on the commonalities and divergences of these two perspectives and the consequences of using one or the other approach in the study of JDMS.

Keywords: embodied cognition, ecological dynamics, common coding, affordance, representation, self-organization

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INTRODUCTION

Thinking about embodiment is as old as psychology itself. One of the founders of psychology, William James, stated early in his psychological writings that.

> the world experienced comes at all times with our body as its center, center of vision, center of action, center of interest. Where the body is is "here"; when the body acts is "now"; what the body touches is "this"; all other things are "there" and "then" and "that." (James, 1890, p. 154).

We argue that when embodied choices in complex environments such as sports are considered, taking two recently discussed theoretical approaches into account can be useful. One of them assumes that there is mediation between a person and the environment through mental representation, and the other assumes direct contact between a person and the environment and thus no need for mental representation. Both approaches will be used to contrast interpretations of embodied cognition in sports. This paper is submitted as part of the special issue on radical embodied cognition, and thus, we first define and position these theoretical approaches in this discussion, then provide a detailed analysis of these divergent theoretical positions, and finally reexamine empirical evidence in two published articles from the perspective of the approach that was not followed in the original analysis.

Back in 1890, James was an early voice attempting to challenge what was then the accepted separation of the body and the mind, as put forth by Plato (428/427 to 348/347 B.C.) and, more explicitly, by Descartes (1596–1650). Today, if one searches for the term "embodiment" or "embodied cognition," more than 10,000 papers from the last 50 years and 100 of reviews in a dozen disciplines can be retrieved from the Web of Science, a body of literature that is growing at a rate of at least three papers a day. This trend shows that the consideration of motor control, and thus the importance of the body and its movements, is now far from being the "Cinderella of psychology" (Rosenbaum, 2005) it once was.

Radical embodied cognition approaches assume that the functioning human body itself constitutes a cognitive process (Chemero, 2011; Jacob, 2016). According to Jacob (2016), there are at least two approaches. The "basal radical" approach principally denies the existence of representations and challenges computational approaches to cognition. We refer to this as taking a direct contact approach. The "constructive radical" approach describes bodily processes with regard to their functionality and as a component of cognition. In some cases, a constructive radical approach accepts that there can be a mediating role of mental representation (see Newen et al., 2018, for a range of positions). In sports, this discussion can be traced back to the motor-action controversy (Beek and Meijer, 1988), in which a rather representational approach based on motor program theory (Schmidt, 1988) and an ecological approach to movements (Reed, 1988; Warren, 1988) that excludes representations from its explanations were pitted against each other.

It should be noted that we, the authors, differ in regard to the radicality of our embodied cognition perspectives. We agree that the mental representation approach could just as well be defined as a moderate embodied cognition perspective, contrasting with the more radical direct contact approach. Below, we define and elaborate of the concept of representations. From the moderate perspective, cognitive processes are based on or are at least moderated by sensorimotor processes (Barsalou, 2016; Zona et al., 2018). The conceptual basis of this paper is that empirical findings indicating effects of sensorimotor processes on cognitive processes cannot be ignored (Goldinger et al., 2016) or explained as an "epiphenomenon" (Topolinski, 2010). Further, following the frequently cited review "Six views of embodied cognition" (Wilson, 2002), we agree on Wilson's major assumption of cognitive processes being situated, dynamic, and functional and serving actions or being expressed by actions. The mental representation and direct contact approaches differ in whether they see a strict separation of the environment and the person. In the following, we argue that an embodied cognition perspective is needed to understand the dynamic interplay between people and the environment.

The present conceptual analysis focuses on the level of the individual (or group) performance domain (Rohrer, 2007) using mainly observed behavior of individual athletes in sports. Further, we define the representational and direct contact embodied cognition perspectives (see next section) such that an organism is a direct contact agent to the extent that its behavior is an immediate (not mediated by mental representations) function of its ongoing interplay with the environment by perception-action coupling and "a representational decision maker to the extent that its behavior is an immediate function of various higher-level states downstream from its perceptual states" (Schulz, 2018, p. 14).

REPRESENTING THE WORLD AND THE BODY OR CONTACTING THE WORLD WITH THE BODY: CONTRASTS BETWEEN EMBODIED COGNITION PERSPECTIVES

Clarification of the Notions of Representation and Person-Environment System

In the present paper, we refer to embodied cognition as: "Cognition is embodied when it is deeply dependent upon features of the physical body of an agent, that is, when aspects of the agent's body beyond the brain play a significant causal or physically constitutive role in cognitive processing" (Wilson and Foglia, 2017, p. 1). When considering judgment and decision-making as embodied cognitive processes, we refer to the concept of embodied choice: "The central statement of embodied choice is the existence of bidirectional influences between action and decisions. This implies that… the action dynamics and its constraints (e.g., current trajectory and kinematics) influence the decision-making process" (Lepora and Pezzulo, 2015, p. 1). We extend this definition by adding that also previously learned movements can influence current decisions (Raab, 2012).

About the notion of representation, it is important to differentiate the representational and nonrepresentational perspectives. We argue that representations within the research field of embodied cognition represent "neither states of the body per se nor states of the environment per se, but rather relations between body and goal" (Pacherie, 2018, p. 377). Naturally in science, there are multiple variations of such definitions as well as levels to describe them (Bickhard, 1998;

Haselager et al., 2003). For the context of this paper on embodied cognition, we do not use a narrow concept of representations, considering them amodal or encompassing abstract symbols as often discussed in computational-representational theories of cognition (see Dempsey and Shani, 2015 for a discussion). We rather follow what is called an action-based approach: "An action-based approach to the problem of representation holds actions play a central role in shaping cognition" (Dempsey and Shani, 2015, p. 833). The content of such representations does facilitate prospective regulations of actions and can be discussed for instance as common codes (Prinz, 2013), or events (Hommel, 2015), instantiated at a neuronal level as a group of mirror neurons (Rizzolatti and Craighero, 2004).

The notion of person-environment system has implications for the concept of mental representation. Some approaches to psychology tend to be based, tacitly and explicitly, in a number of dualisms of which mind-body is the most common, thus the need for an "embodied cognition" manifesto. For ecological psychology (e.g., Richardson et al., 2008), these multiple dualisms are reflections of an overarching dualism: the view that organism (such as persons and other animals) and environment are logically distinct, separate systems (Järvilehto, 1998; Turvey and Shaw, 1999). The dualist view localizes cognitive processes in one's mind and brain not in the surrounding. Consequently, a separation between person and environment originates explanations of cognitive activity centered at the organism. However, when organism is considered separate from environment, and the partial system (organism) represents the whole system (i.e., environment and organism: representations that give meaning to the stimuli from the environment and representations of how to control organism's actions), there is a tendency to find explanation for behavior through variables (mental representations) that are beyond direct observation (Richardson et al., 2008). Contrary to this tendency, for the ecological approach (Gibson, 1979), the person and environment are mutual (one implies the other) and reciprocal (one could not exist without the other), in that the existence and influence of organism on environment and the existence and influence of environment on organism are both equivalent and complementary (Gibson, 1979; Richardson et al., 2008). More than just mutual and reciprocal, however, organism and environment are a combined whole (Turvey, 2009), such that the organism-in-its-environment (i.e., the organism-environment system) should be taken as the proper unit of analysis for studying behavior (Turvey and Shaw, 1999). Järvilehto (1998) suggests that, from this perspective behavior is a reorganization of the organism-environment system, not an interaction of organism and environment; and cognitive processes are different aspects of the organization and dynamics of the organism-environment system, not local processes of the organism. This is why from an ecological approach, there is no need for a part of the system (the organism) to represent the other part, or to represent parts of itself (the body), or representing the interactions between both parts (for example, see Vicente and Wang, 1998, or Turvey and Shaw, 1979, for memory without mental representations; see Turvey and Carello, 2012, for intelligence without mental representations).

A Moderate Embodied Choice Perspective: Embodied Cognition With Mental Representation

In a recent review of different embodiment theories (Gentsch et al., 2016), one representational approach identified was the common coding principle (Prinz, 2013), a prototypical account of embodied cognition with mental representations (see Gentsch et al., 2016 for other representational accounts). It deviates from traditional representational accounts who argue for amodal and independent representations of cognition, action, and perception (Block and Fodor, 1972, for an overview, see Newen et al., 2018). Instead, perception and action are linked by a "common code," meaning that perceptions can be transformed in the mind directly into actions and actions can influence perceptions (Prinz, 2013). The common coding principle is based on James's hypothesis about the anticipation of action goals: That is, anticipated consequences (those to be perceived in the future) guide people's actions (see Mechsner et al., 2001, for an empirical demonstration).

In contrast to common coding, other radical embodied cognition perspectives are anti-representational (Wilson, 2002; Chemero, 2011), but this rejection of representations when explaining decision-making has recently been criticized (e.g., Schulz, 2018). Consequently, other theories have been developed that integrate embodied cognition with a representational account of decision-making (e.g., Schulz, 2018). However, in a recent discussion, representational accounts of decision-making have been associated with costs of representations when deciding. If representations are costly arguments presented in detail in Schulz (2018) doubted that evolution has favored representations for decision-making. The typical argument that representational decision-making is costly is as follows (e.g., Schulz, 2018): Representational decision-making is costly, slow, and needs attention when humans decide. Given that nonrepresentational (i.e., direct contact) decision-making avoids such costs, it has been proposed that evolution favors it. Schulz (2018) refuted this argument by showing that representational decision-making can also be fast and frugal (Gigerenzer and Gaissmaier, 2011), allowing for adaptive behavior as well as neural efficiency and thus evolution favors both representation and nonrepresentational decision-making. One reason why representational decision making can be beneficial is that it allows for more flexibility in choices (Schulz, 2018). A second argument is that fast and frugal heuristics are quick and accurate (Gigerenzer et al., 1999). In short, "the fact that decision rules need to be stored does not affect the ease with which organisms can adjust to changed environments, and it does allow for faster and more frugal decision-making" (Schulz, 2018, p. 183). Thus, representational decision-making is not as slow as often assumed (see below, with the simple heuristic approach, how decisions can be fast and frugal). Finally, Schulz (2018) showed that much decision making is representational to allow for adaptive behavior in the many domains in which choices take place.

Common coding and direct contact alternatives can be compared by looking at the types of tasks in which representations might be needed. Representational decision-making might be more useful for decisions that are deliberate and protracted (e.g., an athlete's decision to retire, made over the course of a month) than for short-term decisions (e.g., a playmaker's allocation decision made in a split-second during control of the ball). This distinction is based on the work of Schütz-Bosbach and Prinz (2007). They separated offline effects from online effects in embodied cognition. Offline effects refer to the self-stored experiences of movements that influence a person's own current decisions in a task even when the person is not moving. Online effects refer to the influence of current information from one's moving body on one's judgment. For example, a soccer coach observing the players on the pitch uses only her offline experienced movements to judge whether a pass or a shot is a good decision, but a player on the field additionally also uses his current (online) movement to decide to pass or shoot. Coaches' and players' behavior in principle can be explained by both representational and nonrepresentational decision-making. As argued above representational and nonrepresentational decision-making processes seem to have been equally favored by evolution (Schulz, 2018) and can both be used adaptively, depending on one's current behavioral needs (see Raab, 2017, for modeling such dynamic and probabilistic behavior).

Representational decision-making is often assumed to rely on mental representations that are determined by content-specific models and perspectives (Gentsch et al., 2016). According to the common coding principle, perception and action share a "common code" and thus are represented together. On the neural level, this common code is reflected in a group of neurons, so called mirror neurons, that are active both when movements are observed and when movements are performed (Prinz, 2012; Barsalou, 2016). Formally, this can be denoted as "higher-level state S in organism O has content C if S has the appropriate structure to allow O to detect the world's being in state C" (Schulz, 2018, p. 16).

How can these mental representations be used in decision-making in sports? Raab (2012, 2017, in press) has tested the simple heuristic approach and extended it to judgment and decision making in sports (JDMS). The simple heuristic approach is based on indirect perception: People perceive cues in the environment that they choose to use according to the cues' validity, that is, how often a particular piece of information (cue) was helpful in good choices before (see Gigerenzer, et al., 1999, for formal descriptions, behavioral tests, and modeling approaches). Simple heuristics have three building blocks: a search rule, a stop rule, and a decision rule. Those building blocks are thus a demonstration of a representational approach to embodied cognition.

How does one apply simple heuristics to sport decisions? One approach has been formalized (see Raab and Johnson, 2004) and illustrated with a basketball example: Comparing two (or more) options (e.g., allocating the ball to different team members) with multiple cues (e.g., distance to the basket, distance to the next defensive player), the decision maker (i.e., playmaker) should start with the cue with the highest validity, for example, pass to the teammate who is closer to the basket. If two teammates have the same cue value, that is, both players are perceived about equally distant from the basket, move to the next cue, such as the distance between the teammates and the closest opposing defense player, and continue until one cue has a positive cue value, for example, one teammate is less defended, and then play to that teammate. This logic has been applied to different sport situations (Raab, 2012, in press). The problem of the costs of representational decision-making is partly solved in the simple heuristics approach because rules are fast and frugal but still mostly accurate (see Gigerenzer et al., 1999). The main argument for why heuristics are efficient cognitive processes has been empirically validated, for instance, in the less-is-more effect (Gigerenzer and Brighton, 2009; for further evidence, see Schulz, 2018, p. 171). The less-is-more effect indicates that the expected proportion of correct inferences is higher when less information is used to decide. A good example of the less-is-more effect is the recognition heuristic, which has also been applied to sports, for instance, predicting the winners of women's and men's tennis matches in the Wimbledon tournament (for an overview see Bennis and Pachur, 2006). Using the recognition heuristic, one would predict for each competing pair that the recognized player will win. Studies applying such a test of recognition to predict a competition's outcome have so far usually compared the predicted against the actual outcomes of a game. They have shown that the recognition heuristic can describe betting behavior quite well (e.g., Serwe and Frings, 2006; Scheibehenne and Bröder, 2007). Furthermore, the accuracy of predictions based on recognition are equal to, or even better than, experts' seedings (an equation to calculate rankings of all players using multiple and weighted parameters) by the tennis associations, which are based on much more complex algorithms and a greater amount of information (Scheibehenne and Bröder, 2007).

We now illustrate this point by discussing selected articles with embodied cognition in JDMS. The rationale for selecting prototypical empirical illustrations for the conceptual analysis is to prepare a comparison of the mental representation and direct contact perspectives of embodied cognition. If the bidirectionality between perception and action holds (common coding principle), then training that activates the motor system (blindfolded to avoid visual perceptual input) should result in better visual perception. Casile and Giese (2006) asked participants to learn awkward walking by setting the arm movements to a phase of 270° to the gait pattern which is very far of the normal gait behavior. After participants had learned this pattern, they were shown point-light displays of these movements and movements in which the degree of arm movement, and gait pattern was not 270° and were asked to identify movements (e.g., those that belonged to the class of 270° phase) or to discriminate stimuli (e.g., two movements are the same or different). Interestingly, participants from the motor-learning condition were better at identifying and discriminating movements without any visual-learning input. Good motor learners were better than poor motor learners in the perceptual identification and discrimination tasks, indicating that the quality of the learned movements influenced the perceptual judgments. We argue that these findings demonstrate, from an embodied cognition perspective, how the motor learning without visual input can influence visual task performance.

The empirical benefits of motor training in the above study for perceptual judgments can be interpreted from a common coding perspective as follows: A person seeing point-light displays of movements will predict the action effects of those movements. If the person has experience with those movements, the solely perception of movements will activate the corresponding action *via* the common coding. The additional activation of the motor experiences allows that person to perform well in the identification and discrimination tasks (for similar effects and explanations that refer to internal models from our laboratory, see Kennel et al., 2014a,b; for other laboratories, see Tucker and Ellis, 1998; Calvo-Merino et al., 2006).

Is empirical evidence from Casile and Giese (2006) enough to say that the motor system affects the visual perception of movements and thus is the action-execution part of the decision-making process? This question is presented because the learning experience in the Casile and Giese's study is a typical offline effect of embodied cognition, as described above. The learning was prior to the perceptual tasks in which participants were not moving. Whether action execution is part of the decision-making process, when online movement choices are conducted, was investigated by Aczel et al. (2018) in arm movements toward two targets. The authors differentiated whether the movement to one of the targets was influenced by the ongoing movement toward the target or by the movement costs associated with changing the movement direction to select a different option. In two experiments, they showed that energetic movement costs influenced target choice but not the ongoing direction of the movement. The authors interpreted these experimental results as evidence against an embodied-choice hypothesis. We assume that the experimental evidence does not violate embodied-choice principles as the energetic costs of changing movement trajectories between two arm movements are small. However, in other real situations, such as climbing, for example, action execution would most likely be part of the decision-making process because the climber's survival could depend on it. Another line of evidence is based on neuroscience showing that the motor system is active during deciding between two targets (Cos et al., 2011). In sum, we argued that a representational approach of embodied cognition could be used to interpret empirical findings of sport choices which we call an embodied choice perspective (Raab, 2012).

Ecological Dynamics of Decision-Making: Embodied Cognition With Direct Contact

As recently mentioned by Baggs and Chemero (2018), basal radical embodied cognitive science has two approaches: the ecological approach and the enactivist approach. Both approaches reject representations as a needed construct to explain cognition. However, the ecological approach starts from the organization of the environmental properties (action possibilities) to explain how they constrain behavior for individual actors. The enactivist approach tends to start from the individual, characterizing the individual's exploratory, self-regulating behavior. Here, we present a particular ecological framework that combines dynamical systems with Gibsonian ecological psychology: the ecological dynamics framework (Araújo et al., 2006, 2017). This approach stresses the primacy of individual-environment relations in understanding cognitive processes. The link between a performer and his or her environment is the proposed starting point for understanding how performers move about, select routes, decide with whom to cooperate, and compete with adversaries in the actual competition environment (see Correia et al., 2013, for a review of studies exemplifying how). In the representational view, the behavioral expression of those decisions is not at the heart of cognition because behavior is assumed to be an implementation of a mental representation (see Adams, 1987 for a review).

For ecological dynamics, the regulation of behavior as an expression of a cognitive process (Gibson, 1979) should not be attributed to one part of the individual-environment system (i.e., the performer) but to this entire system. The selection of actions is embodied (i.e., it is shaped by the skills and characteristics of the body) and embedded (i.e., the performer-environment system as the unit of explanation) in the performance context; that is, it is not based on inferences or other mental processes but on the interplay between whole-body action and perception in a sport performance environment (Araújo et al., 2017). Cognition is embodied (in a body) and embedded (in a context) so that detecting event information related to spatiotemporal characteristics specifies body forces and torques required in goal-directed action (Richardson et al., 2008). This understanding of cognitive processes embraces the notion that major influences shaping individuals' behavior are from the social and physical environment, as well as from their own action-perception skills (Araújo et al., 2017).

In ecological dynamics, decision-making behavior is defined as transitions in a course of action, where cognitive processes are necessarily constrained by the evolving environment-individual system (Araújo et al., 2006; see below). The current state of this system is the result of a history of interactions that constrain the immediate action. In this way, current performance is shaped by memory and past experience (memory need not be based on representations; Gibson, 1994; Reed, 1996). An individual's behavioral history as well as the skills and characteristics of the body channel action to a landscape of possibilities for behavior (affordances) offered by a particular environment. The field of affordances reflects the multiple possibilities for action that stand out as relevant for each individual in a particular situation because of his or her specific training, skills, and experience in related tasks (Rietveld et al., 2018). This means that the affordance landscape is constrained not only by the past (e.g., what is in memory) but also by the future, that is, by task goals, actions' path dependency toward which the current action may be directed (not necessarily expectations or beliefs about the future). Behavior is an expression of skill, and at the same time, it is an expression of how the environment draws the individuals into it and solicits actions (Gibson, 1994; Reed, 1996).

Measures of action, therefore, are a direct expression of cognition, contrasting with indirect expressions of behavior (and cognition) such as neurophysiological or verbal correlates (Araújo et al., 2017). Neurophysiological and verbal correlates are not measures of cognition. They are nervous systems activations or reported words from which researches make inferences about cognitive processes. In turn, action is directly measurable, and if action is an expression of cognitive processes, then cognitive activities can be directly measured. Skillful behavior is constrained by its past (path dependency) and its future (affordances), resulting in action being an ecologically flexible process (self-organized, emergent) to satisfy impinging constraints. When a system establishes a state due to the dynamic interactions among elements within the individual-environment system (no element guiding the organization), the state is self-organized. Self-organization, as the term suggests, is not caused by external (e.g., coaches' instructions) or internal (e.g., the mind) processes, but it is instead generated by interacting constraints within the individual-environment system (not directed by one single constraint). Actions (e.g., a lateral pass in soccer) that emerge (when a pass line suddenly appears) are different from the components that make up the system (e.g., the pitch, the ball, teammates, the legs of the performer) and cannot be predicted solely from the characteristics of those components. Consequently, many sorts of solutions to achieve a sport task goal can emerge given the many different ways its elements can interact under the same constraints. But instead of being a random process, or in the other extreme, a process that is internally programmed (determined) in advance, performers are perceptively attuned to affordances (by detecting information) that guide self-organizing action toward achieving a task goal (Davids and Araújo, 2010).

A major challenge is to understand the ability of individuals to perceive the surrounding layout of the competitive environment on the scale of their own body and action capabilities (Fajen et al., 2009). As performers move with respect to their surroundings, opportunities for action persist, emerge, and dissolve, even if the surrounding environment remains stable. Subtle changes of action can give rise to multiple and marked variations in opportunities for subsequent actions. The dynamic process implied in the perception of affordances provides the basis by which performers can control their behavior prospectively (Montagne, 2005). However, cognition has traditionally been defined as the information processing that produces mental representations, even though there are no direct experimental observations of internal representations (i.e., representations cannot be directly measured). Probably, the definition of cognition proposed by Stepp et al. (2011) best captures the embodied-embedded nature of the ecological dynamics perspective: "Cognition is the ongoing, active maintenance of a robust organism-environment system, achieved by closely coordinated perception and action" (p. 432). This understanding of cognition emphasizes its nature as an activity and its close relationship with perception and action. From this ecological perspective, characteristic cognitive capabilities accommodate the physical principles of dynamic systems (involving time evolution of observable quantities according to, for example, thermodynamic principles). Dynamical systems can offer tools (e.g., nonlinear physics and differential equations) to understand cognitive processes (see Araújo et al., 2014, for an example of mathematical modeling of dynamic decision making in rugby using differential equations, and see Araújo et al., 2019, for a review of studies in sport performance).

An important nuance is that affordances are only accessible to individuals with the necessary skills to act on them. This is why the characteristics of a performer, such as skill level, are of paramount importance. Rietveld et al. (2018) defined "skilled intentionality" as the performer's selective openness and responsiveness to a field of affordances. During the act of perceiving, the hands, legs, ears, or eyes of a performer can explore the available information in an environment, searching the surrounding, structured energy patterns. These structured energy patterns (i.e., information as it is ecologically defined), such as the light reflected from the soccer ball, are an environmental resource to be exploited by active players (Reed, 1993). From this viewpoint, the process of perceptual attunement brings a readiness to affordances that without skill would not be accessible, since it is skill that opens possibilities for action to an individual (Rietveld et al., 2018). This implies that while affordances may exist in a performance or practice context, athletes' skills facilitate their use of specific affordances (which invite actions, Withagen et al., 2012). Importantly, successive actions are modulated by the individual exerting her or his agency by intentionally driving, the performer-environment system dynamics at appropriate points to yield a trajectory (Withagen et al., 2017). In turn, these local dynamic interactions are coupled to larger scale dynamics, guiding the formation of the behavioral trajectory over longer time scales.

Reciprocally, the longer term dynamics could influence the short-term interactions (and thus highlight specific affordances), for example, by altering environmental conditions. Because a behavioral trajectory is assembled anew on each occasion, the action sequence is historically contingent and variable, allowing for the flexibility observed in ordinary action sequences. From this viewpoint, decision-making emerges as athletes search in a field of affordances to arrive at a stable, functional solution, emphasizing the performer-environment reciprocity (e.g., Araújo et al., 2014).

CONTRASTING INTERPRETATIONS OF RESULTS OF EMBODIED COGNITION

In the following, we evaluate two JDMS papers that were chosen to serve as prototypical examples of the perspectives on embodied cognition and their contrasting interpretations of effects discussed in this article. This allows us to illustrate our argument that the interpretation of empirical results can be based on either concept. Each paper is an example of decision-making research in sports using one of the embodied cognition perspectives. Both papers demonstrate how research questions are formulated in the JDMS domain from an embodied perspective, provide phenomena that need explanation, and present two established paradigms that are used for research in JDMS. More specifically, the paper by Correia et al. (2012)

was chosen because it tests a nonrepresentational hypothesis by means of assessing the dynamics and organization of action patterns for explaining choices. The paper by Pizzera (2012) was chosen as it provides a theoretical background of a representational embodied cognition approach using discrete choices and long-term motor experiences as the source of the judgmental process. Choosing these papers allows us to contrast the approaches and leads to a discussion of their commonalities and divergences in the "General Discussion and Conclusions."

Comments on Correia et al. (2012)

The study by Correia et al. (2012) showcases the dynamic systems approach within JDMS from a direct contact perspective using skilled young rugby players. In this study, the distance between two defenders in rugby influenced the movement parameters of the attacker and the probability of the outcome being to tackle (defender wins) or to try (attacker wins). The authors' explanation was that movements are used flexibly and that movements adapt to changes in the environment such as the defenders' behavior. The authors further argued that the defenders' movement displacement trajectories express different "preferred relational states" in this attacker-defender system and that the attacker reacts to the defenders' movements. Further, they argued that decision-making behaviors (e.g., the decision where and when to run) emerged as a function of changes in attackers' spatial location during the performance.

From an embodied choice account of embodied cognition (Raab, 2017), the environmental constraints (distance of defenders) would be used by the attacker to predict the action consequences of his own movements, which would be updated dynamically. A choice to move in one of the movement directions to pass a defender can be modeled as an embodied choice as follows: The attacker uses predictions to prepare his movements. This means in terms of common coding, the anticipated response consequences that are based on his own sensorimotor representations. The hypothesis of the study would remain the same: Experts will be good at predicting the outcome of specific choices. The interpretation of the results, however, would change: The explanation of what movement will be produced and how would be based on the interaction of the sensorimotor and the cognitive system and would rely on a representation in a common code between perception and action.

From the simple heuristic perspective, the perception of the distance to defenders is defined as a valid cue for making the choice. The use of the cue changes dynamically depending on the speed and the movement trajectories of the attacker. If the cue "largest distance to the next defender" is the most valid cue, the athlete would choose the direction that would increase the distance to the next defender. Another interpretation is that the distance between an attacker and defenders is used by rugby players to predict players' actions and internally model them (see Raab and Johnson, 2004 for an experiment and a computational model in basketball).

Comments on Pizzera (2012)

Pizzera (2012) studied regional gymnastic judges and the quality of their ratings of gymnastic performances. The task of these judges was to perceive and evaluate gymnasts' performances according to predefined scoring rules. In her introduction, Pizzera highlighted that research has shown that perceptual judgments can be constrained by judges' position in respect to the gymnast and that the ability to perceive the information sources is another key aspect. This attunement to sources of information seems to be developed by exploring the task through different means (i.e., by performing it and by observing others perform it). Pizzera's study aimed to clarify if judges who had performed the judged tasks and/or had experience observing others perform such tasks would achieve higher quality in judging gymnasts' performance in such tasks than someone without this motor and observational experience. The assessment of such experience was based on a questionnaire that asked, for instance, how many years they had performed gymnastics, how many times they watched gymnastics per week, and if they could perform a specific task on the balance beam.

After judges learned how to use an online video test at their personal convenience, they rated gymnasts performing a specific balance beam task. The quality of the judgment was compared between judges who could perform the task themselves and those who could not. Pizzera found that adding general motor, visual, and judging experience did not improve the prediction of judgment quality. But judges benefited from their own motor experience on the specific balance beam task, increasing the quality of their judgment. Specifically, Pizzera found that judges who practiced the specific task they were asked to judge focused "on aspects that allowed them better perceptual sensitivity" (p. 606), and she suggested that studies focusing on eye-movement strategies may clarify the mechanism underlying this advantage. Pizzera concluded that this development of judgment expertise was achieved through structured and effortful adaptation produced by training.

From an ecological dynamics perspective, we could not agree more with this explanation of the findings of this study. Indeed, to understand how a specific performance is achieved, one has to understand how the performer interacts with the task, and how the history of such interactions (experiences produced by training) perceptually attunes the performer to the relevant sources of task information that allow the performer to attain task goals. This is an explanation fully aligned with ecological dynamics, in that it is based on embeddedness and embodiment of the motor experience, in this case acting to perceive, attuning the judges to the relevant task information sources.

What is somewhat unclear, in the sense that it does not follow from the previous line of argumentation, is the second part of Pizzera's discussion. She argued that the results from the study suggest that judges "use their personal experiences as information" (see abstract, p. 603) to improve the quality of their perceptual judgments about gymnasts' performance in the studied task.

Why would a judge's perceptual sensitivity to the environmental information presented by a gymnast performing a specific task need to be combined with another, apparently unrelated, source of information, namely, personal experience from the past? A more parsimonious explanation would be to hypothesize that performance judgment is based on perceiving what is relevant from the environment directly, rather than perceiving this information and then, by means of some obscure process (that cannot be directly measured), combining it with some consulted information from the past, with the goal of making the externally detected information more accurate—exactly the same information that had been detected directly since the beginning. Then Pizzera continued to emphasize this less parsimonious explanation: "It would be interesting to investigate whether judges with and without motor experience differ in how they internally represent the performed routine or memorize the skills" (p. 607).

There may be some difficulties following through on this suggestion. The first is how to scientifically capture how judges internally represent the performed routine and how to detect differences in mental representations. Would it be based on indirect measures of what mental representations might be, such as brain activation areas or verbalizations about such mental processes? (see Araújo et al., 2017, for a discussion). Then one would need to justify how such mental representations are related to the task that the judges are performing (how the internal represents the external), how using such internal information benefits the perception of the gymnast's performance, and finally how such internal and external sources of information are combined. Beyond the demonstration of such processes, there is another difficulty, which is to justify why such a detour (i.e., consulting internal information and then combining internal and external information) is necessary, if what seems to explain expertise is precisely the perceptual attunement to the relevant sources of (external) information (the gymnasts performing the task). This capacity to make high-quality perceptual judgments was achieved by the judges interacting with the environment over time, by means of a structured and effortful adaptation (attunement) to the task environment (motor and observational training), as Pizzera indicated. So, why search for mental representations if expertise in perceptual judgment is based on the discrimination of and sensitivity to environmental sources of information, developed through the particular bodily interactions with the performance environment? In short, a very straightforward explanation can be provided by an ecological dynamics approach to decision-making, namely, that judges with experience in perceiving and acting (i.e., performing) a task are perceptually attuned to the relevant constraints for performing that task.

GENERAL DISCUSSION AND CONCLUSIONS

It should now be obvious that there are some commonalities and key divergences in the two embodied cognition approaches presented here. Starting with the theoretical commonalities, there is the body as the starting point for understanding cognition. For both approaches, the body shapes the knowledge of the world, where perception and action, that is, the means by which organisms contact the world, are intimately linked. The mental representation and direct contact perspectives of embodied cognition share the understanding that choices are not idealistically rational, and humans do not search for optimization or follow optimal rationality norms. Rational choices as advocated in some areas of psychology ignore bodily information for decision-making and thus are too mechanistic to be useful for JDMS. We envision a perspective here that highlights embodiment as a key to understanding JDMS, a perspective that defines success not in terms of optimality but in terms of adaptiveness in a current situation.

It is on how the body contributes to this ecological success that the two approaches diverge. For the embodied choice perspective, there is a place in the body (the brain) where perceptual representations match with action representations (i.e., common coding principle). But for the ecological dynamics (i.e., direct contact) perspective, there is no need for such representations because perception (and action) is direct (not mediated by representations): The patterns of ambient energy (i.e., information), such as light reflected from objects, directly inform what is there for organisms capable of detecting such energy patterns (e.g., humans do not have perceptual systems that detect infrared light). And therefore, action enables perception, and perception enables action.

Theoretically, both perspectives should be able to explain how long-term experiences with specific movements help to advance peoples' decision-making in sport and more specifically how referees, athletes, and coaches decide. Correia et al.'s (2012) study was originally presented from an ecological dynamics perspective. Here, we interpreted the results from an embodied choice perspective. Pizzera (2012) interpreted her findings from a common coding, representational perspective as part of a research program in her dissertation. The alternative interpretation argued from a nonrepresentational perspective. Both studies were used for the present conceptual analysis to simply illustrate the starting point for theorizing, rather than demonstrate a falsification approach that can be accepted or rejected by an empirical test. The conclusion of this conceptual analysis is that mental representation and direct contact theoretical accounts of embodied cognition can coexist when explaining JDMS, to further refine the different theoretical views on embodied choice phenomena that are far from being understood.

From a methodological point of view, the two approaches converge in the search for representative experimental task designs (Brunswik, 1956), in the sense that the tasks represent the circumstances about which the findings are aimed to generalize. However, for the embodied choice perspective, the measurements are mainly discrete (e.g., the score of the judge's quality in each trial), whereas for ecological dynamics, the measurements are mainly dynamic (e.g., the time series of each trial's trajectory of an attacker when facing the defenders near the try line). This methodological difference also highlights a theoretical difference: that decisions are not all-or-nothing snapshots but continuous adjustments and transitions of a performer within his or her environment (Correia et al., 2013). On the other hand, current models in JDMS are often probabilistic and dynamic (e.g., see Raab and Johnson, 2004, for a dynamic representational approach in JDMS).

Another line of divergence is the use of the representative design concept itself. From the perspective of the simple heuristic approach to embodied cognition, representative design (see Brunswik, 1956) refers to the tasks in an experiment needing to be randomly selected (as participants are) from the general distribution and class of tasks in the environment. From the ecological dynamics perspective, representative design means that the actions and environmental constraints need to be representative of the person-environment interactions in the real world (Pinder et al., 2011). We recommend providing a more detailed description of task selection for designing studies (see Johnson and Raab, 2003) or including environmental constraints (Chow et al., 2011) such as time pressure within a task (Musculus et al., 2018).

From a practical point of view, the authors agree that, for instance, for a coach, the implementation of these theoretical perspectives in practice may be overall similar. Consider some practical implications of Correia et al. (2012), p. 249: (1) "Participant behaviors are flexible and adapted in a goal-directed manner to current task constraints" and (2) "simple practice task constraint manipulations, such as varying number of players involved, distances between players (e.g., defender-defender initial conditions) and field dimensions, powerfully influence emergent decisions and actions of performers (attackers and defenders) in team games." What does taking a mental representation or a direct contact perspective mean for selecting tasks in experiments and in training? Both perspectives would potentially agree that training needs to dynamically produce actions under constraints. This is in contrast to modular approaches to training, such as implicit perceptual training (Jackson and Farrow, 2005), cognitive training, such as in steps-of-decision-making training (Vickers, 2007), and repetitions of movement, such as out-of-water swimming movements. One potential distinction would be that for the embodied choice approach, a relevant part of an exercise would be to ask the performer to verbally generate options for the next action in a particular task, whereas for the ecological dynamics approach, the focus would be on acting upon perceived affordances; that is, instead of highlighting the generation of action options, the performer should perceive task affordances and act upon them. For example, Seifert et al. (2017) demonstrated that previewing a climbing route allowed climbers to become perceptually attuned to affordances. Once acted upon, they applied adjustments and revealed new information that, in turn, indicated further adjustments and so on toward goal achievement. Implementing these theoretical perspectives in experiments and practice sessions in sports could lead to a better understanding of individual differences in performance through the systematic use of multiple task variants and multiple tests (training measures), somewhat in line with recent methodological recommendations in the study of cognition (e.g., Boogert et al., 2018).

How can JDMS be improved by applying embodied cognition with and without representation? We illustrate this process with talent selection and development. Talent selection refers to sport systems in which youth are selected to become professional. In German soccer, this process involves about 2 million boys, of whom only 600 are selected by the youth academies of soccer clubs, and only about 30 receive a contract with a professional club thereafter. Talent development refers to the training, education, competitive team assignment, and transfer policies affecting these young players over time until they become professionals (de Oliveira et al., 2014).

From the mental representation perspective of JDMS, concrete applications need to refer to a specific framework. For instance, from the simple heuristics referred to above we would select and train talent on learning and selecting between different heuristics (de Oliveira et al., 2014). This talent strategy would not test cognitive and motor processes in isolation but rather would test sport- and context-specific heuristic use, often with separate measures of perception and attention (search and stop rules in heuristics), "what" decisions (which movement to perform), "how" decisions (how to perform a movement), and motor performance (decision and execution rules in heuristics). A talent selection camp in which decisions to select or not to select a talent would be based on a list of heuristics. Knowing for each relevant heuristic how well talent is able to use it at a specific age makes it possible to use the heuristic for talent selection (Musculus et al., 2018). For talent development, this simple heuristic perspective would not isolate cognitive and motor training but would integrate them (Jackson and Farrow, 2005).

The direct contact approach offers the principles for designing effective practice tasks and learning activities to develop talent and prepare them for the demands of competitive performance (Chow et al., 2011). In ecological dynamics, the development of judgment and decision-making in talented athletes is, in part, the result of their responsiveness to the design, types, and modes of activities experienced during practice and play (Araújo et al., 2004; Davids et al., 2017). Such activities offer the athletes the possibility to learn how to be adaptive in detecting information and realizing affordances in different performance environments. Gaining expertise in this important part of athletic development involves *selectivity* since not all affordances are "for good" for all performers (supporting goal achievement) and some can lead to problems such as negative outcomes, injuries, or poor health (Araújo et al., 2017). This connotation of affordances has some important implications for developing expertise and talent in sports. Competitive sports performance environments provide manifold action possibilities, which are uniquely relative to an individual (Gibson, 1979), requiring high levels of specific experience, development, skills, and intentionality to utilize such affordances (Rietveld et al., 2018). For example, opportunities for action in a performance environment that can be perceived and realized by a professional athlete will differ from those used by a recreational athlete (Chow et al., 2011; Davids et al., 2017). These ideas imply that task constraints, in an affordance landscape (Rietveld et al., 2018), can be designed to *invite* specific actions from different athletes, depending on personal constraints, such as skill levels. Therefore, creativity in practice task design is warranted in presenting affordance landscapes in sports that are dependent on the athletes' expertise levels.

In conclusion, this conceptual analysis argues for a pluralistic account of the variety of processes implied in embodied cognition in sports. There is no single theory that can explain such complex processes and we follow what has been studied in science in general, that it may depend on the starting point of your theoretical account what and how researchers think representations are important within embodied cognition (see Hesslow, 2002; Svensson and Ziemke, 2005). The work presented may offer contexts and programs for further investigation, which can either contrast with or refine hypotheses from researchers accepting or rejecting mental representations. Despite our theoretical preferences, a hidden goal that brought us together was to focus the discussion on the explanation of the phenomena, highlighting that there are very different frameworks in place and that the discussion can go beyond computational power or sample size. The simple reason for this: JDMS is a fascinating domain to search for embodied cognition explanations.

AUTHOR CONTRIBUTIONS

The authors equally contributed to the structure, theoretical position, and writing of the manuscript.

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Search Strategies in the Perceptual-Motor Workspace and the Acquisition of Coordination, Control, and Skill

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In this paper we re-visit and elaborate-on the theoretical framework of learning as searching within the perceptual-motor workspace for a solution to the task. The central focus is the nature of search strategies to locate and create stable equilibrium regions in the perceptual-motor workspace and how these strategies relate to the emergent movement forms in the acquisition of coordination, control, and skill. In the ecological theory of perception and action, the enhanced stability of performance occurs through the attunement of the perceptual systems to the task dynamics together with modifications of action as task and intrinsic dynamics cooperate and/or compete. Thus, through practice in this search process, individuals adapt to the pick-up of task relevant perceptual variables and change their movement form according to the stability of the performed action and its outcome in relation to the task demands. Contemporary experimental findings have revealed features of the search process given the interaction of individual intrinsic dynamics in the context of task requirements and principles that drive the change – e.g., exploitation of more tolerant task-space solutions and emergence of compensatory mechanisms. Finally, we outline how the search strategy framework relates to traditional learning-related phenomena: including the dynamical pathways of learning, learning curves, factors of learning, individuality, motor development, and sport and rehabilitation interventions.

Keywords: motor learning, ecological psychology, dynamical systems, coordinative structures, intrinsic dynamics, individual-differences, exploration

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INTRODUCTION

The study of motor skill acquisition is central to understanding the underlying processes of how behavior comes to be the way it is as well as to providing principles of the best approaches to intervene on it. Skill acquisition is, in our view, however, less an "acquisition" and more a "transformation" or "change" of the individual abilities to act in searching within the environment in pursuit of a task goal.[1] This search process reflects and gives emphasis to the continually evolving dynamics of perceptual-motor processes in learning.

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[1] Because of tradition, nevertheless, we will still call it as "skill acquisition."

In this paper, we revisit and expand on the Search Strategies Approach to skill acquisition (SSA) (Newell et al., 1989). The general theoretical backdrop draws on the ecological theory of perception and action. The SSA provides a theoretical and operational framework to examine the time-dependent processes of change in motor and perceptual variables, both within and between trials, over a range of task categories.

Traditional Assumptions in Skill Acquisition: Group- and Task-Based Learning

We can summarize the majority of early and current views on skill acquisition as theorizing on how movement capabilities of a group evolve given changes in the constraints of a task condition. Two assumptions are held in studying skill acquisition this way: that the summaries of the group represent changes of each individual and/or that the task conditions are sufficiently constraining for learning to be of the same kind for all individuals.

In this way, individuals homogeneously learn the skill, converging in behavior. It means that when comparing, for instance, constant and variable practice (Schmidt, 1975; Moxley, 1979; Braun et al., 2010), individuals within each group are more similar than between groups and that the process of change observed through the average behavior is representative of all individuals.

The assumption of within-individual processes being represented by between-individual measures disregards the fact that motor learning and development (skill acquisition) are non-ergodic processes (Molenaar, 2008). That is, skill acquisition is a non-stationary process and each individual does not necessarily have the same dynamics (e.g., Liu and Newell, 2015). Individuals differ in initial conditions (Zanone and Kelso, 1992, 1994; Kostrubiec et al., 2012) and demonstrate distinct patterns to the pathway of change in learning (Rop and Withagen, 2014; Pacheco et al., 2017; Pacheco and Newell, 2018b).

The assumption of convergence in behavior also disregards that the majority of tasks may be solved in a number of ways (i.e., redundant tasks, see Bernstein, 1967; Latash, 2012). For this reason, it is not necessary that individuals must converge to the same solution (learn the same pattern) even in similar task conditions (Pacheco and Newell, 2018c).

A framework on skill acquisition should avoid such group- and task-based assumptions in order to unravel the principles underlying the phenomenon. In considering learning as searching, one understands that differing initial conditions afford different perception–action relations leading to distinct pathways in learning. Also, similar initial conditions diverge through the discovery of informational variables and the link between these and actions. In both cases, redundancy in the task allows these different pathways to diverge.

Skill Acquisition and the Ecological Theory of Perception and Action

The ecological theory of perception and action offers a set of relevant constructs for motor skill acquisition. It provides a principled view on how the biological system interacts with its environment to achieve goal-directed behavior. **Figure 1** shows the basic schematic (adapted) from Warren (2006) which illustrates the interaction between agent and environment through perception and action that gives rise to the emergent stable behavior at the coordination level. In incorporating the open non-linear nature of such interaction, the theory considers how intrinsic tendencies in perception and action of the individual change through interacting with the task requirements and environmental informational variables (Shaw and Alley, 1985). Additionally, it avoids the use of abstract internal processes to explain observed behavior as information for change (Fowler and Turvey, 1978) can be identified in the interaction between individual, task, and environment.

However, in our view, the current findings and propositions on perceptual-motor skill acquisition are not sufficiently integrated. The empirical work on different initial conditions of learners, for instance, is captured but only in a single paradigm (see Kostrubiec et al., 2012). Moreover, how different pathways emerge considering influences beyond the intrinsic dynamics has received limited attention. Another example is that perceptual learning – which has great influence on skill acquisition as a whole – has largely been considered in a separate literature (e.g., Withagen and Michaels, 2005; Bingham et al., 2014; but see Michaels et al., 2017). **Figure 1** documents the different thematic directions of skill acquisition that the ecological theory has influenced.

The present paper builds-on the SSA to perceptual-motor learning. It sees skill acquisition as a search process in the perceptual-motor workspace (tendencies in perceiving and acting; intrinsic dynamics). The search process, then, induces modifications in these tendencies altering the movement capabilities of the individual; namely, skill acquisition. The SSA approach is within the more recent developments on ecological theory that already holds that the principles of acquisition cannot be derived from averaged results (dismissing between-individual variability, Withagen and Chemero, 2009) but in the commonalities that emerge from the differences between individuals. This view on acquisition encompasses divergent dynamics between individuals and holds the potential to unify the different foci presented in **Figure 1**. This paper presents current developments in search strategies together with how they relate to different foci of the contemporary motor learning literatures.

SEARCH STRATEGIES APPROACH

The view of processes of change as search comes from an evolving broad perspective over many fields of study [see Hills et al., 2015 for a review]. We build here on the perspective of motor learning as the process of searching within the perceptual-motor workspace for a solution to the task requirements (Newell et al., 1989, 1991; Newell and McDonald, 1992; McDonald et al., 1995). The SSA was developed from the early ideas on complex systems by scholars of the former Soviet Union (Gel'fand and Tsetlin, 1962; Bernstein, 1967) and subsequently the evolving tenets of the ecological theory of perception and

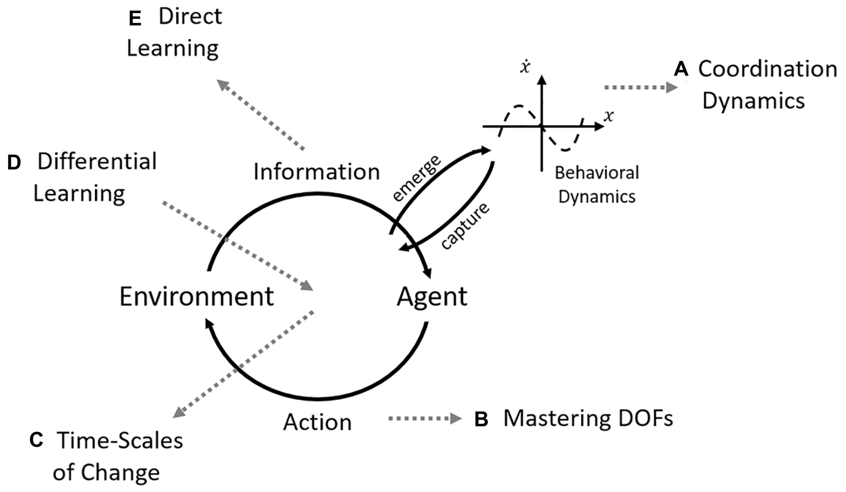

FIGURE 1 | Focused efforts under DST on skill acquisition over the years. The central scheme is composed of the interaction between agent and environment through perception and action that is captured and gives rise to the coordination dynamics (adapted from Warren, 2006). The gray dashed arrows point to the different "themes" that emerged in investigating each aspect of the central scheme. **(A)** Coordination dynamics focused on the change of the intrinsic dynamics in practice (e.g., Zanone and Kelso, 1994; Kostrubiec et al., 2012); **(B)** there was a round of testing the freezing/freeing degrees of freedom (DOFs) hypothesis of Bernstein (1967) (e.g., Vereijken et al., 1992; Mitra et al., 1998; Newell and Vaillancourt, 2001); **(C)** formal analyses on the performance curves observed in motor learning (Newell et al., 2001, 2009); **(D)** the differential learning approach focused on concepts of random variability, stochastic resonance, and others to provide an intervention paradigm (Schöllhorn et al., 2009); and **(E)** the direct learning theory (Jacobs and Michaels, 2007) developed direct hypothesis on how perceptual learning would occur. Note that although all these approaches emerged from DST, they need to be integrated into a single framework (e.g., how does mastering the DOFs interact with performance curves studied in the time-scales of change?).

action (Fowler and Turvey, 1978; Gibson, 1979; Kugler et al., 1980; Turvey et al., 1981). The central focus of SSA is the means to locate and create stable and unstable equilibrium regions in the perceptual-motor workspace together with how these strategies relate to the emergent movement forms in the acquisition of coordination, control, and skill (Newell, 1985; Newell et al., 1989).

Search

It is important to define what we consider as *search* behavior. Searching is characterized as systematic patterns between/within trials over time that emerge from the interaction between individual and environment in pursuit of the task goal. That is, patterns emerge from the search for solutions within the perceptual-motor workspace. Searching is the process of learning to attend to informational variables of the task (see Withagen and Michaels, 2005; Jacobs and Michaels, 2007) and modifying actions in terms of these informational variables resulting in changes of the perceptual-motor workspace.[2] It should be noted that search occurs whether the individuals are practicing on their on (the practice is discovery-based) or "guided" or constrained by a coach, a teacher and so on (see the section "Learning Factors Through SSA"). The advance that we aim for is to identify how such systematic patterns emerge from the confluence of constraints.

Note that the approach relies on more than one level of analysis to characterize searching. This follows the long-held view point that there is not a one-to-one relation between movement patterns employed in a given task and the task outcome (Arutyunyan et al., 1969; Abbs et al., 1984; Kelso et al., 1984) and the fact that individuals actually exploit the many-to-one relation available (see Schöner, 1995). Thus, to understand searching in the perceptual-motor workspace, we consider more than the single level analysis of performance outcome. Procedurally, we explore a few key levels of description defined *a priori* in the attempt to identify informational variables (or contexts) that lead to given changes in action together with the actions that constrain perception of a set of informational variables.

An important feature in understanding search processes is the assumption that the observed search patterns are the entry to understanding the learning process. As individuals search through the space of possibilities, they attune to the most useful information and this modifies ways of acting that afford relevant information variables to be detected. Attunement refers to the process of attending to more useful information for the situation at hand[3] while changes in action refer to changes in movement parameters to achieve the required response. This cycle of change on the many spaces, that we will define in the upcoming sections, is what modifies the capacity of perceiving and acting. In observing the emergence of these many systematic patterns in practice, we can understand a number of features. For instance, how individuals find or fail to find solutions; what are the informational variables that allow within-trial, trial-to-trial,

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[2] This can be said to have roots in Bernstein's ideas: "The process of practice toward the achievement of new motor habits essentially consists in the gradual success of a search for optimal motor solutions to the appropriate problems" (Bernstein, 1967, p. 362).

[3] As noted by a reviewer, attunement (and even action changes) might occur without over action. Wilson et al. (2010), for instance, have shown that individuals learned to perform a new relative-phase in bimanual coordination observing others performing without physical practice.

and longer scales of change to occur; and how such systematic changes affect the perceptual-motor workspace.

On this process, we can understand what the aspects of the interaction between individual and task requirements are that lead to divergence during practice and learning. Nevertheless, we hold to the idea that individuals search in terms of attended information and action possibilities. Information is detected through interaction with the task and environment and action possibilities can be characterized. In capturing the commonalities in the individual emergent patterns of search, we seek to understand the general principles of learning.

Spaces of Search: Goal, Task, and Perceptual-Motor Workspace

Perceptual-Motor Workspace

The characterization of *where*[4] individuals search gives rise to investigation of the interaction between organism and task. Gibson (1966, 1979) proposed that the gradient and singular properties of the optic flow field arising from the individual–environment interactions provide the information for perceiving and acting. The theoretical view point of perceptual flow fields was taken to be generalizable to the other sensory systems. Kugler and Turvey (1987) were attracted to the idea that muscle-joint work spaces are organized by perceptual-motor fields that have similar invariant properties that provide information for perceptual-motor control.

In practice, it is postulated that individuals search through this *perceptual-motor workspace*. This is a characterization of the learner's perception and action repertoire identified by stable and unstable possibilities of perception and action. These tendencies constrain, at least initially, how the search occurs, as performance in unstable regions is hard to maintain. The central hypothesis is that the information individuals use to search in the perceptual-motor work space is a macroscopic property defining the form of the layout of the gradient and singular regions emerging from both task-space and perceptual-motor workspace.

In the literature of ecological theory, different terms emerge to describe the tendencies in perceiving and acting. Here, we interchangeably use "intrinsic dynamics" and "perceptual-motor workspace." The latter was coined to characterize the interaction between perceptual and action fields (Kugler and Turvey, 1987) while the former characterizes the emergent tendencies from these interactions (Kelso, 1995). Both, nevertheless, refer to "[...] relatively autonomous coordination tendencies that exist before learning something new" (Kelso, 1995, p. 163).

The most developed formal example in the literature of intrinsic dynamics is the Haken–Kelso–Bunz (HKB) model (Haken et al., 1985) that in describing a system performing oscillatory movements in two limbs demonstrated stability in two relative-phases: in-phase and anti-phase. This model implies that an individual will reliably perform the patterns of in-phase and anti-phase (for low frequencies) as they are stable feature of the intrinsic dynamics of the individual. The same does not hold for the 90° relative-phase which is not stable. For the 90° relative-phase be stabilized as a new attractor in the intrinsic dynamics, practice is necessary (Schöner et al., 1992; Zanone and Kelso, 1992). Note that individuals differ in terms of the intrinsic dynamics, leading to differences already when starting the practice (some individuals present stable performance of the 90°-phase pattern when starting practice, Kelso, 1995). Other approaches to describing intrinsic tendencies of the system to act are shown in **Figures 2B,C**.

Note that all examples provided in **Figure 2** describe "movement" variables and, thus, might be referring only to action tendencies (although see Schöner et al., 1992). There is a current discussion on whether there is a one-to-one relation between informational variables and perception (Withagen and Chemero, 2009) that can be extended to the relation between perception and action as well. Thus, although we are aware that the stable "movements" emerge from the perception-action coupling, the SSA assumes, in line with current evidence (e.g., Michaels et al., 2008; Withagen and van Wermeskerken, 2009; Rop and Withagen, 2014), that individuals can attend to more than a single informational variable. These informational variables vary on how useful they are for control of a given action. Thus, in order to *fully* describe the intrinsic dynamics, one must also consider the tendencies in *perception*. Furthermore, we need to determine whether the action tendencies are modified or not by changes in informational variable being attended. **Figure 3** shows a hypothetical example.

The characterization of the perceptual-motor workspace is challenging. The HKB model holds given the robustness of the phenomenon and the simplicity of the experimental paradigm and model. There are only two degrees of freedom of interest and the model considers a single variable (relative-phase) that is constrained in the 0 to 2π range. Thus, assessing the intrinsic dynamics here appears straightforward: test all possibilities (see Zanone and Kelso, 1992). Nevertheless, if one wants to consider how individuals actually search through movement parameters to find a solution in the HKB paradigm, the task becomes rather complicated (see Michaels et al., 2017; Brakke and Pacheco, 2019). For movement patterns with larger number of degrees of freedom, it becomes almost impossible to even consider all possibilities in action to be tested. **Figures 2B,C** exemplify other strategies that have been used to characterize observed stable action patterns. The complexity of such description is further increased when one remembers that we are not, yet, considering the perceptual variables that can be attended to in such paradigm.

The intrinsic dynamics are task specific and only after a long round of research on the many constraints (biomechanical, physiological, neuronal) that decrease the space of possibilities will a full description be possible. Here, by analyzing how individuals approach a task, we provide a strategy to assess a limited region of the perceptual-motor workspace supporting performance of the task.

The perceptual motor workspace is ever evolving across the lifespan and at the same time is open to the influence of intention. The perceptual-motor workspace is non-stationary. There is a fundamental process via which practice modifies and, in turn is

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[4] Although we refer to *spaces*, the best term probably is manifold. Spaces usually refer to geometric spaces such as the Euclidean space. Manifolds are topological spaces that locally resemble Euclidean space near each point (Abraham and Shaw, 1992).

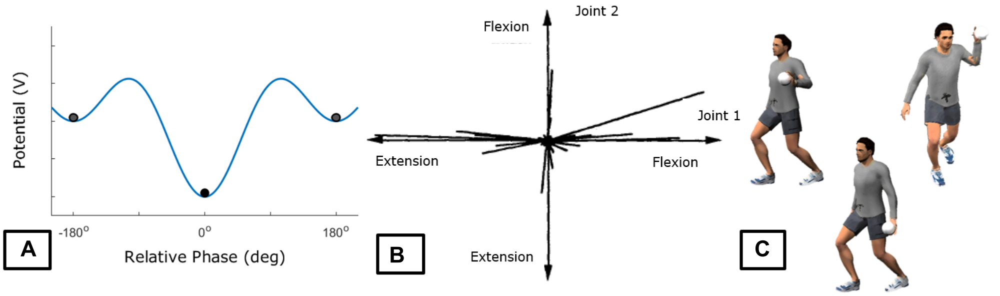

FIGURE 2 | Exemplary intrinsic tendencies. Panel **(A)** shows the Haken et al. (1985) potential function that describes the tendencies observed for a majority of individuals in performing oscillatory motion of two limbs. As observed in **(A)**, the stable patterns that individuals can perform are the 0° (in-phase) or 180° (anti-phase). Panel **(B)** shows the distribution of covariation between two joints in the Krinskii and Shik (1964) paradigm utilized by Newell et al. (1991). There is a tendency to move in certain ways rather than using the whole possible space which is indicative of attractors within the space. This type of plot allows identification of tendencies in action when formal characterizations were not made but relevant variables are identified. Panel **(C)** is a schematic of different tendencies of action in terms of throwing patterns demonstrated in Pacheco and Newell (2018a). This description is qualitative given the difficulty to find relevant variables that characterize the different movement patterns (see Roberton and Halverson, 1984).

influenced by, the dynamics of the perceptual-motor workspace. Through practice and, more generally individual interactions with the environment, the perceptual-motor workspace is modified. That is, action continuously modifies qualitatively and quantitatively the landscape dynamics of the perceptual-motor workspace. The search through the perceptual motor work space changes through attunement to the information in the perceptual array and mapping of movement to it. In the context of action this mechanism of change channels the search strategy within and/or between trials of practice. This complementary process of the perceptual-motor workspace maps to the Gibson (1979) theoretical position that we perceive in order to move and that we move in order to perceive. The relation of search and change in the perceptual-motor workspace, however, is only beginning to be unraveled (see the section "Exploration of the Task-Space and Transfer").

Task-Space and Goal-Space

Although individuals modify their bodily actions in terms of attended information and environmental constraints, there is a goal that also constrains the system into a coherent form. *How* the task goal constrains the behavior can be observed through a formalism called *task-space*.

Simply put, the task-space relates the movement possibilities and performance. Let us use the example of throwing a paper ball into a target on the floor. If we consider variation along a single dimension (e.g., the antero-posterior direction), the place where the ball lands determines the performance directly, $E = l - T_p$ where E is the error, l is the landing position, and T_p is the target position.

This representation of the task-space is overly simplistic if we want to understand how individuals alter their movements. We might get more insight into movement coordination by including variables of the movement that influence directly the outcome of the task. For instance, we know that the release velocity of the ball (assuming constant release position) determines the distance of throw (the landing position) – i.e., $(2v_x v_y)/g = l$, where v_i is the release velocity in the i axis (x – horizontal, y – vertical) and g is the gravity. We can make our preliminary task-space model more complex by introducing the release velocities $E = (2v_x v_y)/g - T_p$. This is still simplistic as it only includes the release velocities of movement, but it provides clues as to how individuals might be organizing their movements. We could go on and try to make the model accommodate more dimensions, but this would not make it easy for visualization or analysis. **Figure 4** shows how the task-space becomes more informative as we add complexity to the task-space for throwing and isometric force tasks.

We usually call v_x and v_y in throwing or f_1 and f_2 in bimanual isometric force (**Figures 4A–D**) as elemental variables. Latash et al. (2007) states that the choice of the elemental variables must conform to the fact that these are independently controllable.

Note that the task-space does not determine how an individual performs. Variability between individuals is quite common in terms of regions of the task-space where individuals perform and, again, is observed in the individuals' interaction with the task. Also, as stated in the section "Traditional Assumptions in Skill Acquisition: Group- and Task-Based Learning," although the task-space is a source of information for individual to achieve the goal, it does not determine how individuals act as, in some situations, individuals must move away from some valleys in the task-space (decrease performance/increase error) to find solutions more appropriate to its own intrinsic dynamics and/or improve performance further.

It could also be that there are transformations that better characterize the way individuals control their movement in a given task. For instance, the throwing paradigm can be characterized by $v^2 \sin(2\theta)/g = l$, where v is the release speed of the ball and θ is the angle of release (**Figures 4E,F**). It could be that some individuals only modify v over time (maintaining θ constant) which would be simple to observe using these variables rather than v_x and v_y as in the other example.

Another important manifold to describe is the *goal-space*. This is the region described by zero error [e.g., $E = 0 = (2v_x v_y)/g - T_p$]. From this, we can see that, when introducing the elemental variables to characterize the task-space, the goal can be achieved in infinitely many ways. That is, the goal-space is not described

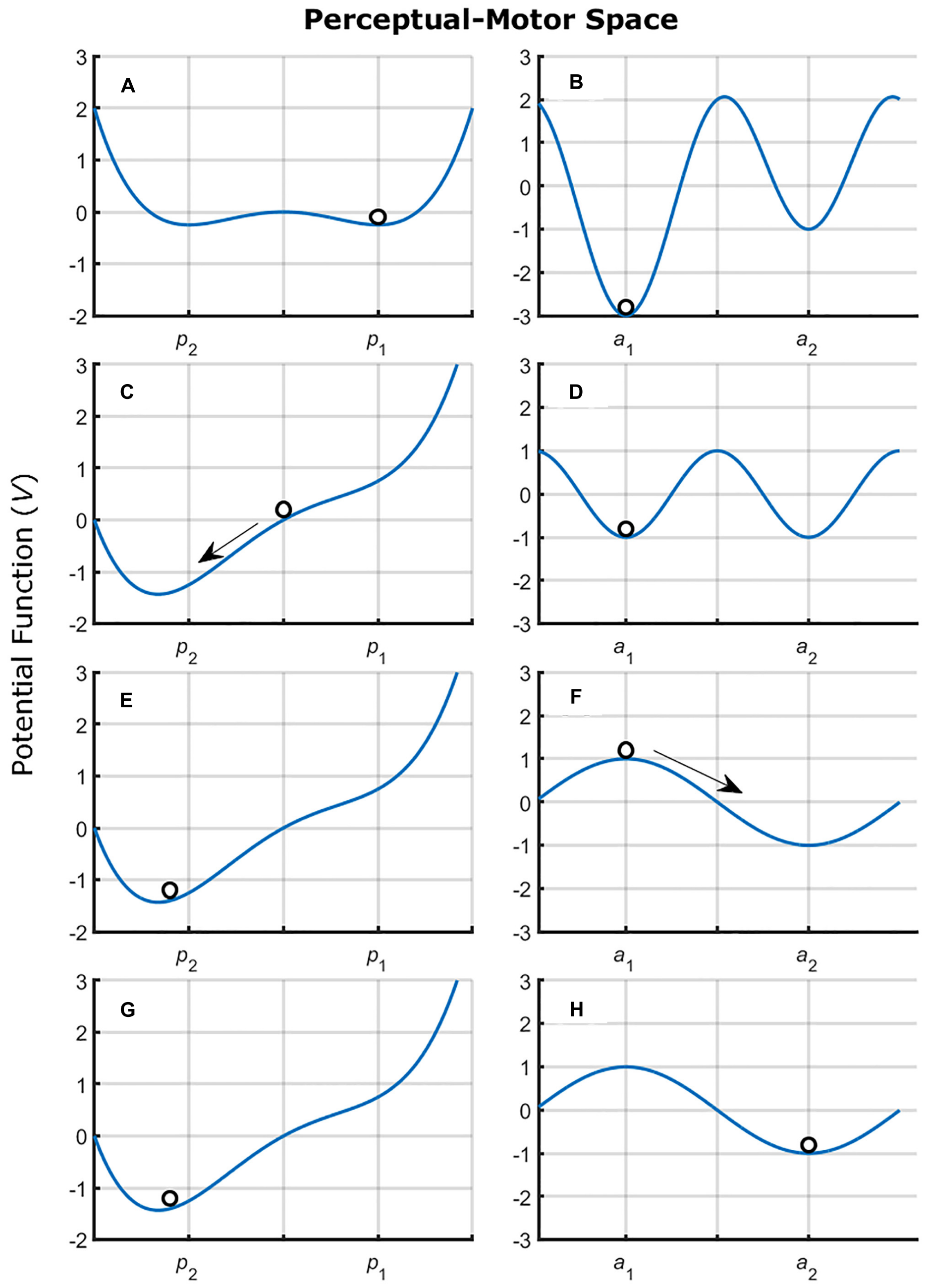

FIGURE 3 | Graphical representation of a hypothetical perceptual-motor workspace. The potential function determines the stable states (valleys). The figure presents changes in the control parameter of the perceptual space **(A,C,E,G)** which results in changes in information attending from p_1 to p_2. The change in informational variable being attended alters the dynamics in the motor space **(B,D,F,H)** changing the stability of the action a_1 and inducing changes to action a_2. The perceptual space was characterized using Tuller et al. (1994) Eq. (1) $V(x) = -kx - 1/2x^2 - 1/4x^4$ and the motor space was characterized using the Haken et al. (1985) Eq. (2) $V(\phi) = -a\cos(\phi) - b\cos(2\phi)$. Both equations were coupled through variable x from Eq. (1), this alters Eq. (2) to $V(\phi) = -x\cos(\phi) - (1 + x)\cos(2\phi)$.

as a single point within the task-space. Many combinations of v_x and v_y allow the same zero-error outcome. This is also the case for the isometric force task presented in **Figure 4D**.

Tasks that have a goal-space with dimension higher than zero (i.e., they are not described by a point) are usually called *redundant* tasks (Sternad et al., 2014). This is because the goal can be achieved in many ways. In these tasks, an individual can exploit the degeneracy (i.e., structure-to-function ratio of many-to-one, Mason, 2010) that the biological system affords and demonstrate motor equivalency. Note, however, that not all tasks are redundant. These would be the tasks that do not include precision, but maximize aspects such as speed, force

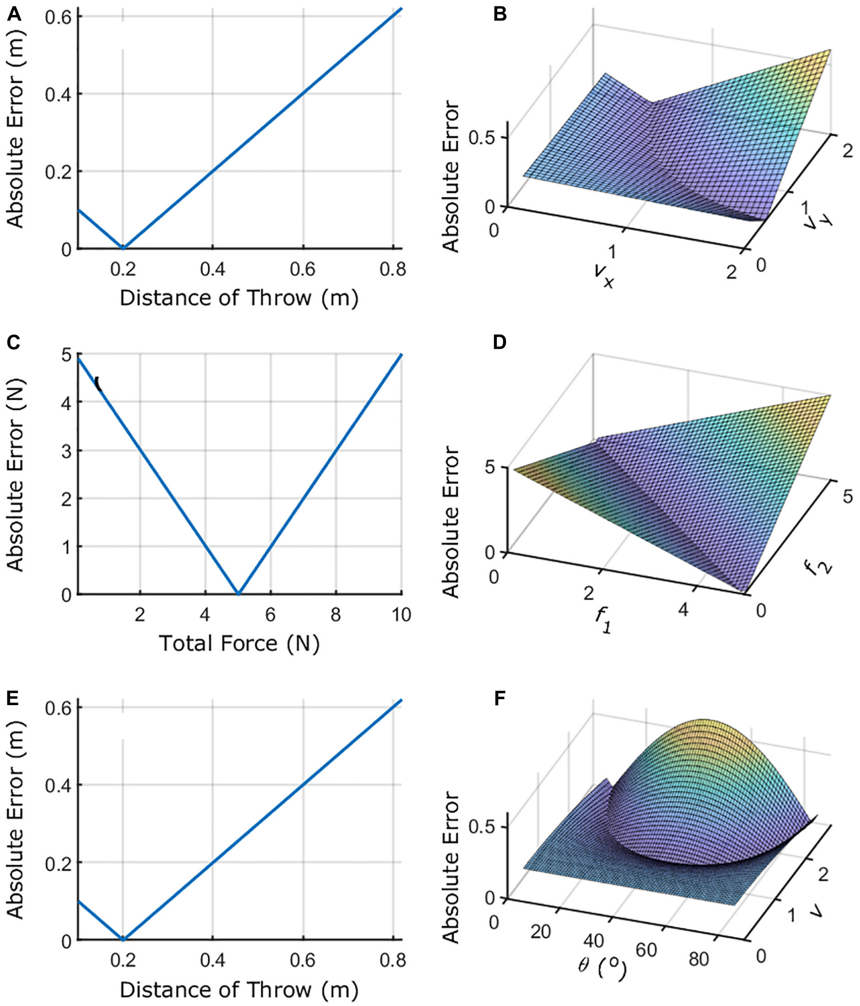

FIGURE 4 | Schematic of task-spaces. Panels **(A,B)** show the outcome/performance and elemental variables (v_x and v_y)/performance relations for the virtual throwing task where initial position is constant, and the target is located at 0.2 m from the initial position. v_x and v_y represent the component of the release velocity vector considering the *x*- and *y*-axes. Panels **(C,D)** show the outcome/performance and elemental variables (f_1 and f_2)/performance for the bimanual isometric force task when the total force target is 5 N. f_1 and f_2 represent the forces exerted by the index finger of each hand. Panels **(E,F)** show the outcome/performance and elemental variables (θ and *v*)/performance relations for the virtual throwing task where initial position is constant, and the target is located at 0.2 m from the initial position considering different coordinates. θ and *v* represent the release angle and speed. For the equations defining each task-space, see the text.

output, etc. For instance, if there is a maximum throwing distance a given individual can reach, given his/her physical abilities and biomechanical constraints, there is theoretically a unique movement pattern that will achieve it.

EMPIRICAL DEMONSTRATIONS OF SSA

In this section we illustrate how the SSA can characterize the perceptual-motor workspace and reveal important characteristics of search through reanalysis of previously published data. The first example comes from a simple application of the throwing study discussed earlier: a virtual throwing task performed on a computerized tablet where participant's movement provides the release velocity of a ball. The goal of the task was to hit a target with the ball (Pacheco and Newell, 2015). The second example comes from an actual throwing task to a target to illustrate how the search can be studied with many-degrees-of-freedom tasks (Pacheco and Newell, 2018c). The third example comes from a re-examination of the within-trial dynamics from a single trial in a bimanual isometric force tracking task (Lafe et al., 2016). Note that, although we provide in each case a single-subject example, the same analyses can be (and were) used to identify differences between individuals.

Virtual Throwing Task (Pacheco and Newell, 2015)

Figure 5 shows exemplary data of the first 30 trials of a participant from Pacheco and Newell (2015). **Figure 5A** shows a decrement in error (absolute distance from target) and **Figure 5B** shows the same data in terms of the task-space using v_x

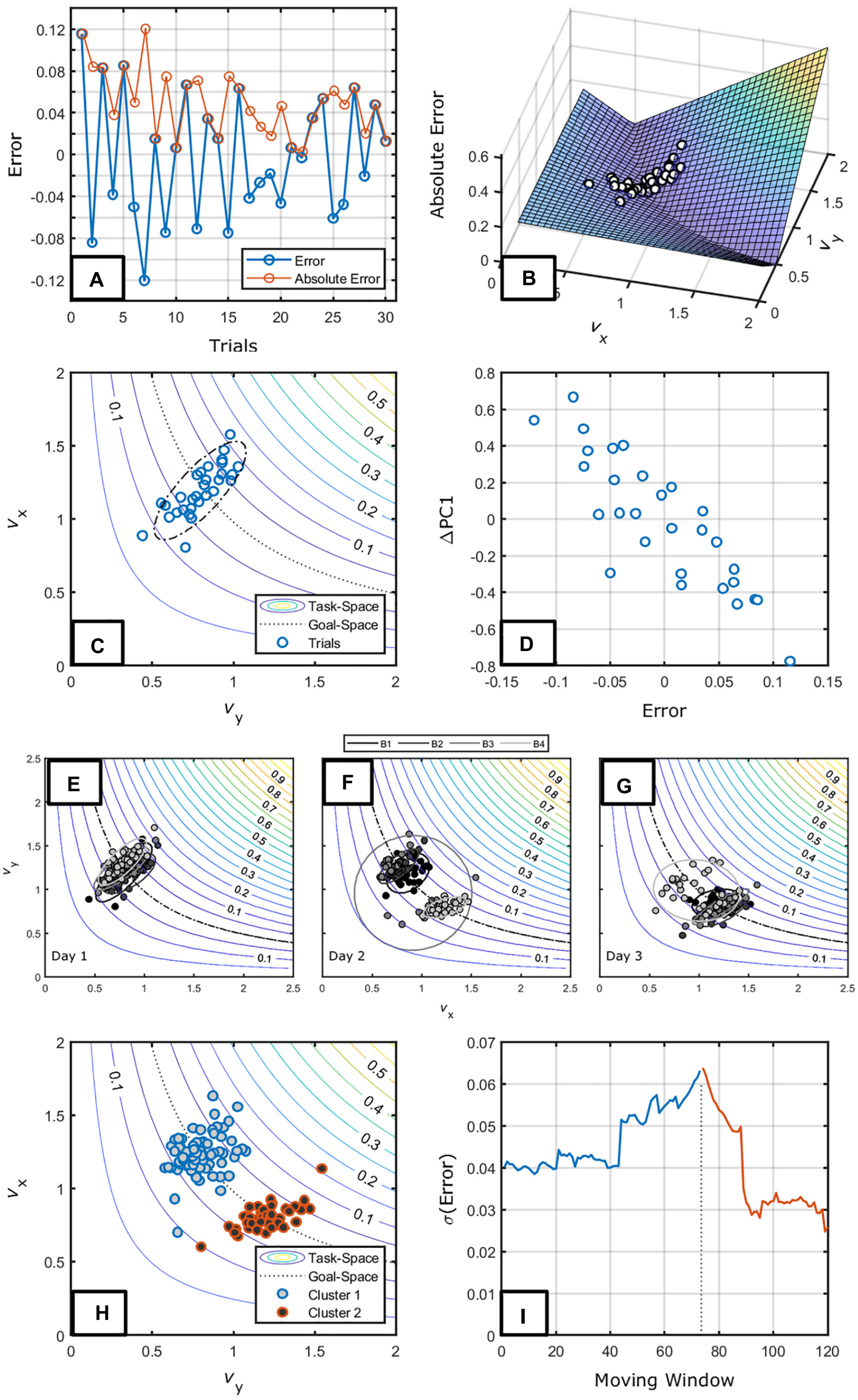

FIGURE 5 | (A) The performance score of an exemplary participant in Pacheco and Newell (2015). The red line and circles represent the absolute error while the blue line and circles represent the errors. **(B)** The task-space plotting the same trials. **(C)** A contour plot showing the same trials and an ellipsoid highlighting the tendency to vary along a single dimension in the plane. **(D)** The relation between change along the main axis of variation of data and error. The data seem to indicate a proportional relation between change and error. Panels **(E–G)** show the long-term changes in distribution of the data in the task-space over blocks of 30 trials for days 1 **(E)**, 2 **(F)**, and 3 **(G)**. Panel **(H)** shows the identified two clusters of release velocities in the task-space for day 2. Panel **(I)** shows the moving window of standard deviation in performance before and after the change from cluster 1 to cluster 2. This shows the increased variation that might have induced changes in coordination pattern employed during the task.

and v_y as elemental variables. Given this plot, we can note a number of features.

The first is that this participant showed a "bracketing strategy" – a tendency to decrease error with alternating signs (Ellis and Wade, 1968; Liu et al., 1999). This can already differentiate different aspects of search since individuals can also demonstrate "creeping" (a decrease in error with the target being approached with constant sign), no change overtime or, even, get worse over time.

Second, this individual varied along a single dimension (even though he/she was free to explore the whole plane). We can infer that this dimension reflects the coordination that this individual is employing in this task. Performing a principal component analysis (PCA), we see that, indeed, this dimension represents 89% of the trial-to-trial variability (**Figure 5C**). A consequence of this analysis is that we can consider that the individual uses *mainly* this dimension to perform the task.

Considering the most prominent axis of variation we can investigate the relation between change and feedback. To do this, we see whether the *change* within the main axis of variation occurred as a function of the feedback received. **Figure 5D** shows the relation and this individual modified the scaling within the coordination mode proportionally to the feedback magnitude ($r = -0.86$, $p < 0.001$). A question that we might ask is whether the second dimension (orthogonal to the main axis of variance) is just inherent variability of the system or it has some role in this task. The former possibility is more plausible: it does not change in terms of performance ($r = 0.10$, $p = 0.609$) and its dynamics does not seem to show any structure (i.e., its autocorrelation shows a white noise pattern).

Does this individual change his/her coordination pattern over time? **Figures 5E–G** show the ellipsoids of data for each block of 30 trials (for the 3 days of practice) and make it clear that indeed the individual changed the region of the task-space as a function of practice. It is interesting to note that this was not a continuous change – there are no trials connecting the two data clouds. One ellipsoid for day 2 and one for day 3 (blocks 3 and 4, respectively) show a large area exactly because it includes both separate data clouds. We can then infer that the subject has two stable coordination patterns apart from each other and, during practice, he/she changed from one to the other. The two patterns are differentiated in **Figure 5H**.

What is the informational variable that induces changes between coordination patterns? More broadly, what is the context that makes individuals stop trying to correct the movement in terms of scaling the same coordination pattern to change coordination patterns? We anticipate that such information is a higher-order variable (variables derived from trial-to-trial KR, see Fowler and Turvey, 1978 and the section "Factors Modifying the Motion Through the Space"). In Pacheco et al. (2017), we found that increased variability predicted change in strategy. Here we see a steep increase in variability (standard deviation of performance) before coordination changes in day 2 (**Figure 5I**) and a fast decrease thereafter that could be indicative of a search for a more stable pattern.

Throwing Task (Pacheco and Newell, 2018c)

We have been studying similar aspects in so-called whole-body movement tasks. Data from the experiment of Pacheco and Newell (2018c) allow such a method to be expanded to many degrees-of-freedom; it increases complexity in the analyses, but the results followed similar patterns.

If we want to characterize this task-space in terms of the release parameters – which would be the smallest set of elemental variables to use – we would not be able to plot it; it has six dimensions (a 3D velocity vector and 3D position vector). Thus, our approach is to find the coordination pattern between these variables before plotting it.[5] **Figures 6A,B** show that this subject produced variation in a single dimension for both velocity and position – which is further confirmed by a PCA (92 and 72% of variance accounted for position and velocity data, respectively). Using these dimensions to build the task-space, as in **Figures 6C,D**, allows exploration of more features of the search process employed by this individual.

First, we could have decreased the dimension even more as this individual had, at least in the first two blocks of trials, a large correlation between velocity and position first PC. However, information on how the individual approached the goal-space (**Figure 6C**) would be lost.

Second, we see that this individual – different than others (Pacheco and Newell, 2018c) – managed to coordinate the release parameters along the goal-space direction. Such a pattern is clearly different than the one shown in the previous example (the tablet task). There, the main axis of variation was used to correct trial-to-trial deviations from the target (**Figure 6D**). Here, the *second* main axis of variation showed a slow convergence to the goal-space.

We can connect these different patterns to hypothesized processes of learning. **Figure 5C** reflects a process of *parameterization* within a coordination pattern – maintenance of the coordination pattern with a change in scaling (Newell, 1985). **Figure 6C** holds parallels to a process called *shift* (Kostrubiec et al., 2012) in which the whole coordination pattern is altered slightly to accommodate new task requirements. That is, the former characterizes change *within* while the latter a change *in* the main axes of variation. A *bifurcation*, where a new solution is stabilized over time, would be characterized by a broad distribution taking shape in the task-space around the transition (see Liu and Newell, 2015).

There is potential to investigate patterns that might be observed at other levels of description – such as the hand trajectory and joint motion. In **Figures 6E–H** there is not much change in the first two blocks of practice. Nevertheless, adaptations in terms of the whole trajectory of the hand in throwing (Cohen and Sternad, 2012; Nasu et al., 2014; Zhang et al., 2018) and joint motion to the task-space (Domkin et al., 2002, 2005) have been described. Little is known,

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[5] Note that there is no necessity for plotting the data. It is, nevertheless, always recommended to understand the nature of the data – even if for few participants – before drawing firm conclusions.

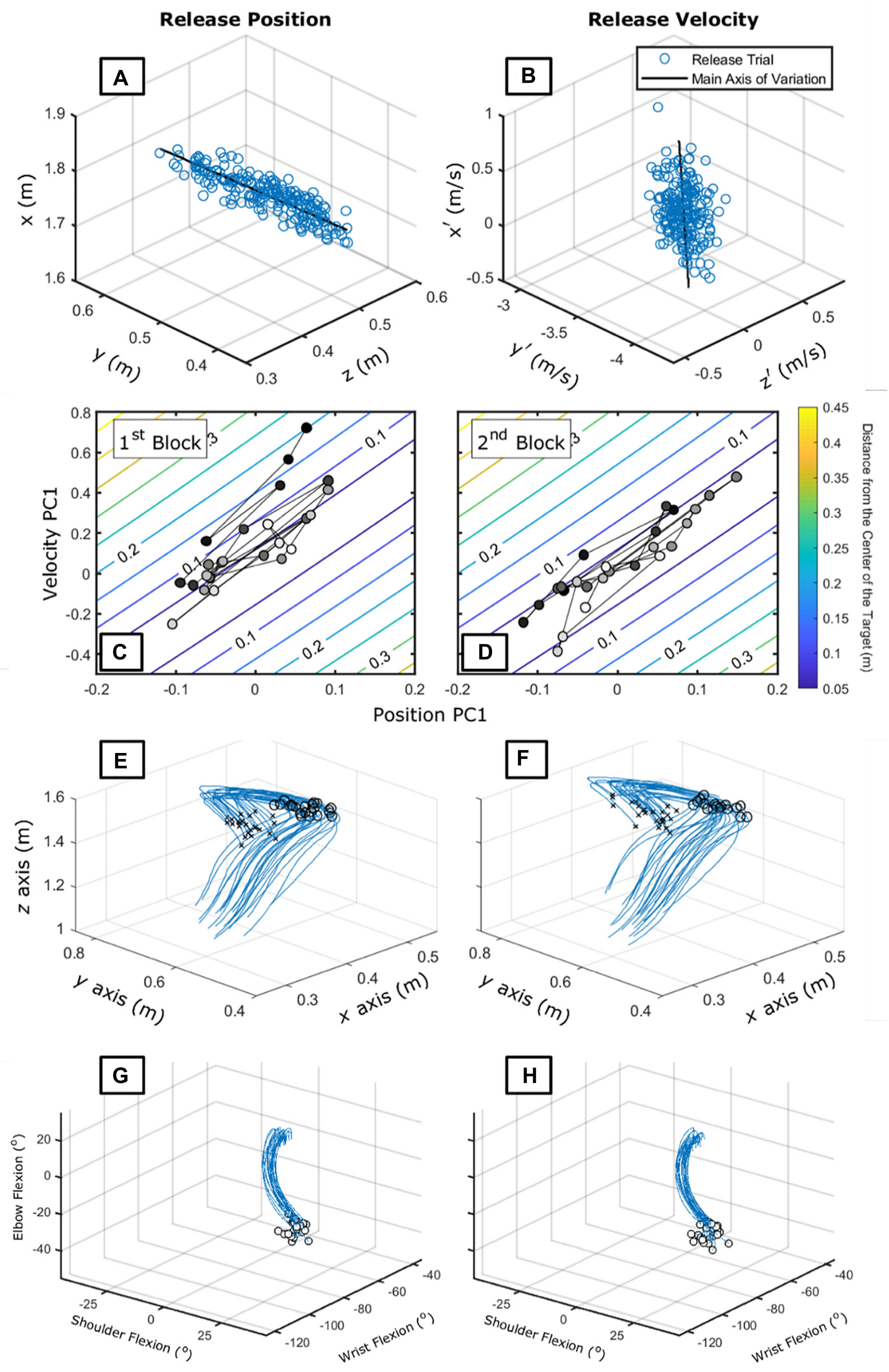

FIGURE 6 | Panels **(A,B)** show the release parameters [position – **(A)** and velocity – **(B)**] of 210 trials of an exemplary participant in his 5th day of practice from Pacheco and Newell (2018c). The black line shows the main axis of variation. Panels **(C,D)** show the task-space plotted in terms of the first principal component of both velocity and position data for the first **(C)** and second **(D)** block of 25 trials. Darker circles represent earlier trials while lighter circles represent later trials. Panels **(E,F)** show the hand trajectory data for the first **(E)** and second **(F)** block of 25 trials. The *x*s represent the beginning of the recording and the circles represent the release position. Panels **(G,H)** show the joint motion relation between shoulder, elbow, and wrist for the first **(E)** and second **(G)** block of 25 trials. The circles represent the release position. For shoulder, 0 degrees mean the neutral position; for elbow, 180 degrees mean full extension; for wrist, 0 degrees mean neutral position.

however, how changes at that level emerge from ongoing perception of informational variables of the task-space.

Bimanual Isometric Force Task (Lafe et al., 2016)

The SSA approach can also provide information in other time-scales of practice (e.g., within-trials). In Lafe et al. (2016), the task was to bimanually press two load cells each with an index finger to maintain a constant total force output while the frequency of concurrent feedback was manipulated. **Figure 7A** shows the data of total force over time through the different intermittent regimes of feedback. The figure shows that the individual had higher error for less frequent concurrent feedback.

Figure 7B shows the change in elemental variables in the task-space. It can be seen that there are two main axes of variation, one orthogonal and one along the goal-space. If we select two intermittency regimes (**Figures 6C,D**), two different coordination modes emerge. We can investigate whether these two types of coordination between hand emerge as a function of information intermittency. **Figure 6E** shows three intermittency regimes and a tendency for in-phase coordination for low frequency of information, 90°-phase for 1.6 Hz of information, and a more distributed relation for higher frequency. Thus, it could be that the frequency of information facilitates different coordination regimes.

Observing **Figures 7C,D**, one can raise the possibility that different coordination modes emerge, instead, as a function of error. That is, a clear in-phase pattern occurs to correct for errors and a more distributed pattern of phases occur around the target. **Figure 7E** differentiates phases according to the error magnitude. It shows that the error and coordination modes relation seems to hold as well. Clearly, as information is modified, the possibility to correct and act employing given coordination patterns is modified (Lee et al., 2019). A more fruitful investigation might be to manipulate the interaction between information and correction requirements.

Insights From the Empirical Demonstrations

These examples show how the process can begin with identifying patterns in data to elucidate the interactions between individual and task requirements that give rise to the observed patterns. A further step would be to manipulate such aspects to confirm that our inferences hold. For now, these diagnostics show how individuals approached the task and we can infer about what were the intrinsic coordination tendencies and ways of interacting with information from task. This kind of information is of great importance to understand how individuals will or can change in a given practice situation. For instance, the individual in the section "Virtual Throwing Task (Pacheco and Newell, 2015)" demonstrated a coordination between the two elemental variables and searched along this single dimension following performance proportionally.

As discussed in the section "Throwing Task (Pacheco and Newell, 2018c)," the SSA can integrate processes of learning that are considered separately. We inferred about processes of learning such as *shifts*, *parameterization*, and *bifurcations*. Shifts in the landscape of the intrinsic dynamics have been analyzed in the realm of between-limb oscillation tasks (Kostrubiec et al., 2012) but have not been investigated in other tasks. Also, the SSA can integrate within a single approach the different forms of change in learning. Shifts and bifurcations refer to coordination pattern changes and parameterizations refer to learning when a given coordination pattern is already in the motor repertoire (Newell, 1985). We also demonstrated changes between already learned movement patterns used to perform the task (**Figure 5H**). Although this is *clearly* part of the process of learning in that individuals explore the action tendencies to find the most useful patterns to a situation, it is rarely discussed in the literature (but see Hristovski et al., 2011; Silva et al., 2019).

In the continuous force task example, the majority of analysis was at a time-scale much longer than the frame-by-frame time-scale of the task. This is because one must consider how corrections, fatigue, force variability, and processes of other time-scales interact to result in the observed pattern over time. The search analysis, however, showed that different coordination patterns (search patterns) emerge as the task allows (information availability) and requires (error magnitude) (see Lee et al., 2019). A practice study on the bimanual isometric force tracking design would provide how the relation between coordination patterns and task constraints emerge from searching, for instance, on a trial-to-trial basis. Clearly, an expansion must be to accommodate all these different time-scales encompassing the limits of perception and action loops to correct the movement (when the type of movement allows search within or only between trials – e.g., ballistic movements).

The SSA still seeks to identify the informational variables guiding the changes or the interactions giving rise to all the systematic patterns observed (e.g., jumps between movement patterns, shifts, etc.). However, even the consideration on limited data encompassing learning as searching provides interesting and fruitful directions for research.

INVESTIGATING SKILL ACQUISITION (CHANGE) AS SEARCH

Dynamical Principles of Change

Here, we evaluate potential principles of search in practice that result from our initial studies and those of others on the topic.

Perception and Action Search Within a Single Level

This first point is less a principle and more an assumption. Considering the many ways individuals can search to achieve a task goal we have been considering that individuals search in terms of a given "level" of analysis in a given time window (considering constant task constraints, see Hristovski et al., 2011). For instance, imagine that a soccer player is in a training situation where his team is attacking, and he/she possesses the ball. He/she can vary parameters within a given kicking movement pattern to score, change between kicking movement patterns, change in terms of the goal of its action such as passing the

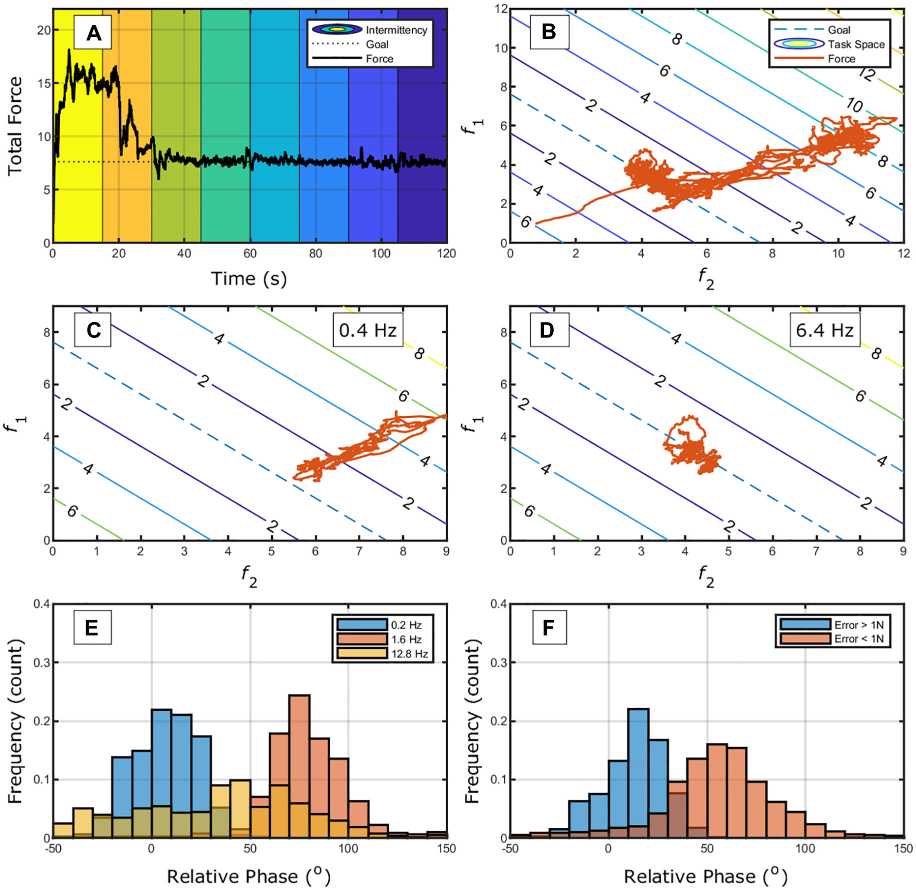

FIGURE 7 | (A) Exemplary trial (first 120 s) of an individual performing the bimanual isometric force task with changing frequency of information (from left to right: 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, and 25.6 Hz, represented by different background colors) from Lafe et al. (2016). **(B)** The same trial now plotted in terms of the task-space. Panels **(C,D)** show the change in the elemental variables (f_1 and f_2) for different regimes of information intermittency; **(C,D)** for 0.8 and 1.6 Hz, respectively. Panels **(E,F)** show the relative-phase distributions for different information intermittency **(E)** and error magnitude in the task.

ball to others or kicking to the goal, etc. In our analysis, we have assumed that he/she might be searching only within a given level at a given time window and its search patterns will demonstrate that – as well it will demonstrate when search occurs in another level.

This assumption is in line with the view that individuals can pick up higher-order variables (informational patterns picked-up over time and space) emerging from the search in the task-space and perceptual-motor workspace. Through this process, information about changing at each level is detected. In explaining the requirement of information to guide motion through the task-space (see the section "Factors Modifying the Motion Through the Space"), Fowler and Turvey (1978) hypothesized that individuals would parameterize a given movement coordination in terms of change in performance (ΔE), would change coordination pattern in terms of the change of change in performance [$\Delta(\Delta E)$ where E means error or the performance in the task]. Gel'fand and Tsetlin (1962) also proposed that $\Delta E/E$ would call for non-local change to avoid local-minima. Thus, individuals might be acting in terms of ΔE (within a coordination pattern) up to the moment that $\Delta E/E$ crosses a given threshold and an overall change in action is required (altering the level of search).

The dynamics of this change could follow the dynamics exemplified in **Figure 3**. That is, the interaction with the space could modify the tendency of an individual in using a given informational variable changing to another variable. In its turn, this would modify the tendency to act to another movement pattern. Although we are not sure about the exact dynamics of such changes, discontinuities in search have been recently observed (Pacheco et al., 2017). We found such discontinuities in terms of the section "Virtual Throwing Task (Pacheco and Newell, 2015)" where an individual, in realizing the inefficiency of a given movement pattern, "jumped" to another one that generated a decreased variability in performance.

A consequence of studying different levels of search is that we have the opportunity to investigate the exploration/exploitation dilemma – the dilemma between maintaining a given strategy with known return and exploring other strategies with unknown but potentially higher returns (Hills et al., 2015, see also, Komar et al., 2019). This aspect is present (as exemplified in the soccer example) but largely disregarded in the motor behavior literature.

Individuality, Equifinality, and Multifinality

A strong inference from SSA is that general principles of learning will be derived through observation of individuals interacting with the task rather than emphasizing the traditions of nomothetic *group* principles (Adams, 1987, see Molenaar, 2004). In our studies, we have found a range of differences between individuals in their initial conditions (Pacheco et al., 2017), motion through the task-space (Pacheco and Newell, 2015; Pacheco et al., 2017), and exploitation of task redundancy (Pacheco and Newell, 2018a,c). These characteristics in search-related processes explained large differences in performance and learning. As these aspects are discussed further in the upcoming sections, we do not provide any empirical example here. The ecological theory of perception and action has motivated studies that highlight individual pathways in motor learning (e.g., Molenaar and Newell, 2010; Kostrubiec et al., 2012), perceptual learning (Withagen and van Wermeskerken, 2009; Rop and Withagen, 2014), and motor development (Thelen et al., 1993, 1996).

A consequence of the discussion on individuality in search is that individuals from the same starting point might diverge in practice finding different solutions for the same motor task: multifinality. Thus, the practice on the same task condition can lead to a variety of solutions, depending on the initial conditions, search patterns, and the allowed redundancy of the task. As highlighted in the section "Traditional Assumptions in Skill Acquisition: Group- and Task-Based Learning," this degeneracy needs to be a feature encompassed by theories of learning.

The approach of Direct Learning (Jacobs and Michaels, 2007) is related to SSA given the common origins in the ecological theory of perception and action but it does not consider the movement characteristics of search or the many expressions shown here of individual variation in learning. An initial assumption in Direct Learning was that the space of search (information space in their terms) determines the search and, thus, can dismiss the large variability between-individuals observed in the initial conditions through the end of practice. The role of variability (Higueras-Herbada et al., 2019) has been amended to deal with situations where the information space cannot guide behavior (Pacheco et al., 2017) but the theory still does not accommodate divergent patterns of change behavior between individuals.

Given the discussion on differences between individuals, it maybe more interesting to try to identify situations that elicit the opposite, equifinality. Overly constraining tasks might elicit this, but a more interesting situation would be one that occurs as a result of long-term practice. This would occur provided that practice is long enough to allow individuals to find a given sweet spot in the task-space (e.g., a tolerant region, see the section "Convergence to Tolerant Regions").

Inherent Variability and Task-Space Perception

Since the early nineties, there is discussion on the role of the inherent variability that is observed over time in behavior – the so-called "noise" (e.g., Newell and Corcos, 1993; Riley and Turvey, 2002; Vereijken, 2010). Some researchers accepted the notion that inherent variability could be just more than a problem that must be minimized (e.g., a mechanism probing the system's stability – Kelso, 1995), some emphasized an exploratory role (e.g., Riccio, 1993) or means to avoid bad solutions (e.g., Schöllhorn et al., 2009), while others still see it as a problem (Harris and Wolpert, 1998).

From SSA, all these viewpoints can be tested directly. In Pacheco et al. (2017), individuals had to minimize an error score that encompassed speed and accuracy while they did not know the weighting of each *a priori*. In one situation, there was a high weighting for speed and almost none for accuracy. Those who started emphasizing speed, because of the high variability resultant of the speed–accuracy trade-off (Fitts, 1954; Schmidt et al., 1979), rapidly perceived the lack of relation between accuracy and score (effect of initial condition!). Those who started emphasizing accuracy, nevertheless, would not perceive the relation provided the *lack* of variation. From the latter, only those who increased speed to the point of increasing variability (again because of speed–accuracy trade-off) perceived the relevant dimension of the task and modified the behavior accordingly. Thus, *inherent variability allows perception of the task-space, especially when variability allows perception of a new dimension of the task-space*.

Nevertheless, this *finding does not occur when individuals must find other solutions within the same dimension*. In a search task (Pacheco et al., in preparation) in which there was a single solution and two non-optimal solutions (local-minima), variability did not predict individuals perceiving the task-space. Two aspects are worth highlighting on this study. First, is that, as observed in Pacheco et al. (2017), some individuals never leave the wrong solution even knowing that they are far from the best performance (or the goal of the task). Second, in regard to inherent variability, this study started with the assumption that both increased or decreased variability could allow task-space perception. From Withagen and van Wermeskerken (2009) and Rop and Withagen (2014), decreased variability would allow individuals to differentiate actual errors from errors that emerge from inherent variability. From Schöllhorn et al. (2009) and Riccio (1993), increased variability would allow perception of the topology of the task-space allowing one to escape from local-minima. We found, contrary to both views, that variability allows perception of the task-space in *some* situations (new dimensions) but not always [see also Chow et al. (2008) on the relation of variability and change between movement patterns].

Inherent variability can also induce qualitative changes in behavior. For instance, Schmidt (1991) argued that receiving feedback close to the goal could induce maladaptive corrections as individuals would try to correct errors emerging from inherent variability rather than *actual* errors. Wolpert et al. (1992) showed that this would not be an issue as individuals usually demonstrate an error-deadzone (i.e., a bandwidth around the target where no corrections are made, see also Blackwell and Newell, 1996). Note that in both cases, variability is assumed to be high enough to be problematic for corrections to occur in terms of error (beyond the simplifying assumption of signal plus noise, see Riley and Turvey, 2002). In Pacheco and Newell (2018b), individuals performed a search task in which they had to find the target by increasing throwing distance in the tablet task [see the section "Virtual Throwing Task (Pacheco and Newell, 2015)"]. One of the targets was located closer than a second one. If variability is determinant in when individuals can or cannot correct in terms of error, the modifications on how to change behavior would occur in the farther target as individuals would vary more with farther throwing distances but not in the closer target. This was exactly what was found. While in the closer target the relation between change and error was proportional (as in **Figure 5D**), the farther target showed a discontinuous relation with a change independent of error when they were approached the farther target (**Figure 9B**).

Emergence of Compensatory Mechanisms

Considering the observed exploitation of body/task redundancy, several approaches have been developed to quantify such exploitation. One of them is the Uncontrolled Manifold (Scholz and Schöner, 1999; Latash et al., 2002). The main aspect posited in the UCM approach is that the control of a given variable will result in a large variation along the uncontrolled manifold (vUCM, redundant space) – maintenance of the relevant variable in the desired state – while the variation in the dimension that represents non-desired changes in the controlled variable will be minimized (the orthogonal space – vORT). In learning, one would expect that this would result in the performance variable representing, at some point in practice, the controlled variable. This would lead to the elemental variables maintaining the performance variable stabilized (large vUCM and small vORT).

The tenets of UCM (Martin et al., 2009, 2019) assume that the structure arises from the decoupling of ORT and UCM spaces by the central nervous system, back-coupling mechanisms, and noise at neuronal and muscular levels. These developments emphasize mechanisms of an already proficient individual in the task. Here we want to pursue an explanation that can explain how this emerges in search.

A first consideration is that the UCM structure emerges differently depending on the task constraints. This is exemplified in **Figure 8** that shows the same tasks as in the sections "Virtual Throwing Task (Pacheco and Newell, 2015)" and "Throwing Task (Pacheco and Newell, 2018c)." Although one could state that in both cases vUCM would be higher than vORT we clearly see that in **Figure 8A** the trial-to-trial variation occurs orthogonal to the goal-space while in **Figure 8B** it occurs along the goal-space.

These differences emerge from the way the task constrains behavior. In the former task, the release parameters are defined by the peak velocity of the movement, while in the latter, the individual can choose when the release occurs in terms of the velocity profile. Recent experiments (Cohen and Sternad, 2012; Nasu et al., 2014; Zhang et al., 2018) have demonstrated that when individuals can choose when to release, they adjust their movement to occur along the goal-space. This makes the moment of release parameter to not matter and, as we observe in **Figure 8B**, to result in trial-to-trial variation along the goal-space. This does not emerge in **Figure 8A** because the task constraints do not afford such a strategy. Thus, *although in both cases UCM-like structure emerged (large variation along the goal-space and small variation on the orthogonal direction), these structures emerged from different constraints*: one emerges from stabilization at the trial-to-trial dynamics of the ORT with its vUCM resulting from drift in coordination while the other emerges from trajectory along the goal-space with no strong trial-to-trial dynamics in the ORT.

A second consideration is whether this compensatory mechanism *always* emerges – being a principle of learning. A firm position is impossible, but we do not anticipate this to be the case. Although the UCM literature in a range of tasks and contexts support this idea (e.g., Papi et al., 2015; Mangalam et al., 2018; Vaz et al., 2019), the UCM-like distribution of the data seems to occur when there is non-desired variability to be compensated. For instance, Latash (2010) has provided examples that in the middle stage of learning the UCM-like distribution might be more pronounced than when individuals are more proficient. Also, special populations demonstrate higher or equal UCM-like distribution than their healthy (or younger) peers (Black et al., 2007; Golenia et al., 2018; Greve et al., 2019). Furthermore, many of our experiments when analyzed for each individual do not show increased UCM and decreased ORT as would be expected (non-published results).

Convergence to Tolerant Regions

Another approach developed to study the redundant many-to-one relation between movement parameters and performance is the Tolerance, Noise, and Covariation (TNC) decomposition (Müller and Sternad, 2004; Cohen and Sternad, 2009). In this approach, the experimenter can quantify how much aspects of variability *cost* to performance during learning. The TNC approach essentially suggests that the search process is driven by exploration for, and exploitation of, regions of the task-space where inherent noise of the system "matters less" (Sternad, 2018). This is captured by the term of "tolerance" within the TNC framework.

The core task employed in this approach is the (virtual) skittles pub-game where individuals throw a ball hanging in a pole to hit a target. This task is of relevance given that, depending on the target placement, there is a more tolerant region of the task-space. In this task, individuals usually converge to this region as they practice. Sternad (2018) has discussed the convergence to the most tolerant region as a general phenomenon in learning that we now consider in the context of searching.

First, *not all tasks have differential tolerance around the goal-space*. We can consider for instance the bimanual isometric force task presented in **Figure 7**. In contrast to the skittles pub game this task provides a linear goal-space. As a result, anywhere along this line maintains the same tolerance to force fluctuations. Thus, convergence to the most tolerant region of the task-space would occur *if* the task has differential tolerance. Second, *even when individuals practiced for a long period (as in Cohen and Sternad, 2009), the experts did not converge to the same region of the space* – some found more tolerant regions than others. Third, *the TNC approach does not account for how such convergence to more tolerant regions would occur in search behavior*.

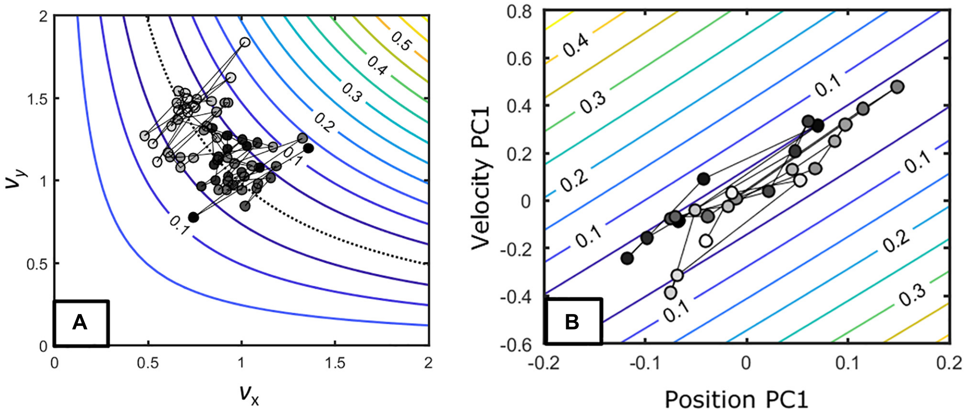

FIGURE 8 | (A) Task-space and trials of an exemplary individual in Pacheco and Newell (2015). **(B)** Task-space and trials of an exemplary individual in Pacheco and Newell (2018c). These figures exemplify how the task constraints might influence how individuals achieve a UCM-like distribution (see the text).

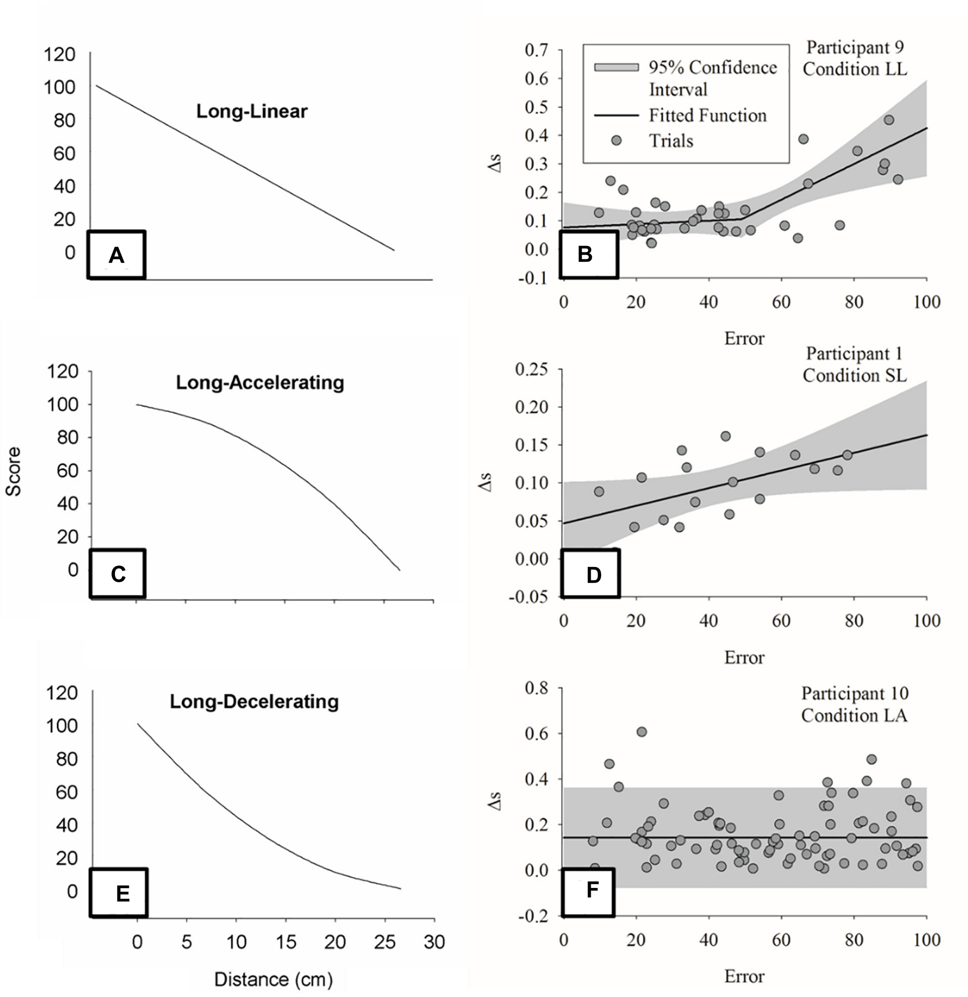

FIGURE 9 | Panels **(A,C,E)** show three task conditions from Pacheco and Newell (2018b). These differ in terms of the relation between error and distance to the target while the target distance itself was constant. Panels **(B,D,F)** show three exemplary data sets that cover the three types of relation between error and change: **(B)** discontinuous, **(D)** proportional, and **(F)** constant.

We, nevertheless, see tolerance as an interesting aspect that can shape how individuals perceive and change during search. Considering the bimanual isometric force tracking task, for instance, how individuals perceive the task-space would be dependent on the interaction of informational and organismic constraints (e.g., force variability, tendencies in action). For instance, increased fatigue in a given finger would lead to increased variability in force production. This could elicit changes in how much each finger contributes in the average (see Singh et al., 2012) demonstrating a change on *where* individuals stay in the task-space given modifications on organismic constraints.

Sternad et al. (2011) sought to differentiate the emphasis on tolerance or inherent variability using the skittles task. In a situation which the goal-space was defined in terms of a single velocity, exploiting lower velocities would reduce velocity-dependent variability, but the most error tolerant region were to be found with increasing velocity. Although it was claimed the results supported the latter, convergence to a common velocity was not observed and there was not the expected velocity-increasing-variability relation.

A factor not considered is that individuals who preferred higher velocities may be searching another elemental variable. In the section "Task-Space and Goal-Space," we highlighted that one can change the task coordinates to better understand strategies (e.g., **Figures 4B,F**). In the case discussed, increase in velocity leads to a reduction in timing variability (Newell et al., 1979) and individuals could be exploiting such relation. Provided the unique case where velocity is free to vary, the timing of release would determine the success of each throw (see also Cohen and Sternad, 2012; Zhang et al., 2018). This could have modified the expected increased-velocity-increased-variability relation (see Pacheco et al., 2019).

One might consider that *inherent variability would afford perception of tolerance in the task-space*. Nevertheless, as highlighted earlier, it is not explicit how variability should relate to perception of tolerant regions – or any other properties of task-space. It is interesting to note that, within the TNC framework, there is an implicit link between noise-cost and tolerance, in that if noise is too great certain regions would be rendered intolerant. The implication is that individuals would find certain regions tolerant while others would not. Thus, an understanding of the relation between intrinsic variability and tolerance in regions of the task-space might explain the divergence in practice.

Learning Curves

The field of motor learning has followed the traditions of psychology and learning theory in the analysis of learning curves (Bower and Hilgard, 1981; Newell and Rosenbloom, 1981; Newell et al., 2006) or, as some prefer to label them, performance curves (Schmidt and Lee, 2005). Although theoretical claims were derived from such curves (e.g., Fitts, 1964; Newell and Rosenbloom, 1981; Taylor and Ivry, 2012), two issues appear. First, the laboratory tasks used have tended to be those where participants can already produce the task-relevant coordination mode leaving the function of change to be about parameterization of a learned coordination pattern (Newell, 1985). Second, the one-to-many relation between performance and movement patterns creates the issue of interpretation of the learning curves. In other words, if a given pattern of performance change can reflect different types of change in movement patterns, how can we interpret the given performance change uniquely (e.g., it relates to a unique "learning stage")? In considering learning as searching, we can show that the different types of learning curves discussed in the literature (i.e., power-law, exponential, and sigmoidal) emerge from the interaction between individual and task-space. Continuities and discontinuities can imply a number of processes in the individual pathways of change (Molenaar and Newell, 2010).

An instructive example is the roller-ball experiment employed by Liu et al. (2006, 2010). This task paradigm requires the individual to maintain an inner ball to keep rotating through movements in an outer ball. Considering the performance in terms of success and failure, there is a variable (imposed acceleration) that individuals must learn to control to achieve success. Although individuals might continuously change this variable, given the relation between this variable and performance (task-space), there will be, inevitably, a sigmoidal performance outcome curve. If the task-space was the only reason for the emergence of the curve, when considering the average acceleration of the ball within a trial as performance measure (Liu and Newell, 2015) the sigmoidal curve should not be observed. For some individuals, this occurred: the change was better represented by a gradual change. Nevertheless, other individuals still presented the sigmoidal curve, implying some other type of discontinuity in the learning process. One could speculate different strategies (see Pacheco et al., 2017) or coordination patterns employed.

Thus, we propose that one can only infer from performance curves if accompanied with properties of the search process employed. The performance outcome score reflects the end product of the search process for the task-relevant solution. The analysis of learning curves, therefore, represents the macro level analysis of the product of the confluence of processes of learning. In this capacity, the performance outcome measure alone does not directly reflect the search strategy and the processes of learning. The performance score needs to be supplemented with other levels of analysis such as those shown here in the experimental examples of searching as learning.

Learning Factors Through SSA

In the following section we discuss traditional factors of learning (e.g., task instructions, practice conditions, etc.) through an SSA lens. Instead of determining a single role for each learning factor identified in the literature, we discuss them in terms of how and when they constrain the search space and/or modify the motion through the space (see also Newell, 1991, 1996).

Factors Constraining the Search Space

A primary aspect for theory and practice is how to manipulate aspects of the task to guide learners to specific aspects of the to-be-learned task facilitating skill acquisition. There are plenty of learning strategies discussed in the literature. For instance, learners can be told to perform a given movement pattern in a specific way (e.g., instructions), mirror an idealized model of the coordination pattern presented visually (e.g., observational learning), or simply discover an appropriate way of performing for themselves (e.g., discovery learning).

Newell and Ranganathan (2010) conceptualized augmented information (such as instructions, demonstrations, and cueing) as providing forward-looking information directing the learner toward relevant aspects of the to-be-learned skill. In this way, augmented information can be thought of as an informational constraint on action. In our terms, this constraint would limit the search space of the task, guiding the learner to the most appropriate space of the task to perform. In some cases, this might be over-constraining. Newell and Ranganathan (2010) suggested that particular movement forms should not be imposed; the teacher should use instruction as a means of facilitating the search for a coordinative solution. Some authors go further in arguing that the absence of specific verbal instruction (discovery learning) would be superior to when instructional demands are given. Discovery learning would provide opportunity for individuals to explore the perceptual motor-workspace to a greater extent (Green and Flowers, 1991; Hodges and Lee, 1999; Hodges and Franks, 2001).

Clearly, the effectivity of discovery learning depends on the task. Several studies have shown that discovery learning in more complex tasks takes longer to find and stabilize a coordination solution – resulting in worse performance overall (Janelle et al., 2003). Additionally, some degree of information constraint is always present as soon as the goal of the task is made clear.

Demonstrations clearly prioritize a given movement pattern and, even though the learner might not exactly reproduce the observed movement, the learner will perform the task in a search space "around" or intending to get to the demonstrated pattern (see Al-Abood et al., 2001). In the same way, cueing direct the learners' attention to a relevant aspect of the task constrain the learner to perform *based* on this aspect. One could question whether such aspect of the task being cued would inevitably emerge in movement as search is allowed to occur without interference.

The area searched in the task-space and perceptual-motor workspace might be modified by the task constraints themselves. Hristovski et al. (2011) presented the summary of findings indicating that, for instance, in boxing a heavy-bag, the distance of the athlete to the bag modified the range of behaviors observed. Their modeling demonstrates how different levels of behavior – from types of punches (movement patterns), to side of punching, to angle of punching within a given movement pattern – emerged as the distance parameter was modified. It would be an interesting avenue of research to understand the relation between changes in level of search in constant task constraints (the section "Perception and Action Search Within a Single Level") versus changes in levels of search in variable task constraints.

Factors Modifying the Motion Through the Space

Beyond constraining, factors of learning might alter how motion through the space will occur. One way is by altering the information that individuals receive about their performance. Here, we will consider mainly knowledge of results (KRs) but the discussion is applicable to different types of information manipulation [e.g., concurrent feedback, knowledge of performance (KP), etc.].

Knowledge of result has historically been viewed as the most effective information to provide the learner of a perceptual motor skill (Annett, 1969; Adams, 1971). The view considered KR to be *sufficient* to strengthen a task relevant reference trace (Adams, 1971) or a schema (Schmidt, 1975), and also intrinsic corrective mechanisms (Salmoni et al., 1984). Much of this interpretation came from single degree of freedom positioning tasks (and the like) that dominated the study of motor control and learning for a period of time. It is questionable, however, whether this role for KR actually holds when considering the whole spectrum of tasks, levels of learning, etc.

In single dimension tasks, KR maps to the single degree of freedom of the positioning task that is to be controlled. Note, however, that if we consider other single dimensions tasks, more than a single trial must be performed to allow individuals to map variations within a given coordination to change in KR when the relation is not explicit. For tasks with more dimensions, KR becomes just a statement of what was done but not what should be done next (Fowler and Turvey, 1978). The question becomes in which direction of the higher-dimensional space of joints, muscles, etc. one should move when KR is, for instance, 5? Can we update reference, schema, and correction mechanisms? The argument holds for other types of information.

Many studies, however, demonstrate the effectiveness of KR in learning. The ecological theory for perception and action addresses the issue. First, individuals are constrained by the coordination patterns that emerge from the interaction between task, organism, and environment (Newell, 1986). Thus, lower-dimensional spaces are to be explored, not the full space of elemental variables. Second, Gel'fand and Tsetlin (1962) and Fowler and Turvey (1978) pointed out that individuals must be able to perceive the properties of the task-space in order to find solutions. This could only occur if, beyond the usage of KR, individuals would attend to higher dimensional variables (e.g., change in KR – ΔKR, relative change in KR – ΔKR/KR, and so on). Thus, the learner must have information for change in the movement pattern (see Newell et al., 1985; Kernodle and Carlton, 1992).

Note that in altering the type of feedback, one constrains the learner to find the means to change in accordance to such type of information. The section "Bimanual Isometric Force Task (Lafe et al., 2016)" showed, for instance, that manipulation of intermittency in concurrent feedback induces large shifts in the coordination between hands as higher frequency of presentation seems to be required for compensation between hands to occur (Lafe et al., 2016, see also Withagen and Michaels, 2005). Another paper helps to elucidate the emergent nature of how KR interacts with action. Pacheco and Newell (2018b), discussed in the section "Perception and Action Search Within a Single Level," included two more target distances that only modified the relation between KR and distance, as shown in **Figures 9A,C,E**. Even though the task was the same, individuals demonstrated different functions relating KR and change in behavior (i.e., linear, piecewise, and constant) depending on the task-space performed. **Figures 9B,D,F** show these different trends. That is, there is not a fixed relation between KR and behavior: it emerges from action and perception on the task-space.

Finally, the factors outlined in the previous section that decrease the available space of search might also alter how individuals search within the space available. By constraining the search space, demonstrations, focus of attention, and other factors alter the initial perception-action coupling employed in a task. As discussed earlier, the way individuals act alters the informational variables they can attend and perception, in turn, delimits the afforded actions. Thus, in changing the initial perception and action coupling employed, these learning factors alter how the ongoing perception-action coupling changes; they alter how search occur. That is, the capacity of acting, which is a function of experience, alters the affordances perceived, which in turn alters the experience in practice.

We have already pointed to some evidence on the importance of initial conditions (Pacheco et al., 2017, see also the section "Individuality, Equifinality, and Multifinality") but Liu et al. (2006, 2010) directly manipulated them. Using the roller-ball paradigm (the section "Learning Curves"), they manipulated the initial speed of the inner ball modulating the initial region of the task-space in practice. They found that, indeed, by altering the initial conditions of the learner, one could predict those who would succeed in the task.

Exploration of the Task-Space and Transfer

So far, we have discussed many aspects that refer to how search allows one to understand change during practice. Nevertheless, if search refers to learning, more than explaining regions explored is necessary. In this section, we briefly refer to our results on transfer as an indication of how search modifies the perceptual-motor workspace.

Our studies have demonstrated that the differences in the end-state of practice – given their different initial conditions and search patterns employed during practice – do predict performance in transfer tests. Two experiments employing the throwing paradigm (Pacheco and Newell, 2018a,c) showed that the learned movement patterns during learning could explain, more than the practiced conditions of practice (variable or constant), the performance in transfer. This supports our working hypothesis in the introduction that searching might be as or more important in learning than the task conditions. An interesting question, then, is how to manipulate task conditions (beyond the current approaches, e.g., Ranganathan and Newell, 2013) to induce the learner to find and learn generalizable solutions.

More interesting, however, is the fact that the patterns of search must be considered – even when the same end-state is observed. Hodges and Lee (1999), for instance, showed that discovery-learning and instructed groups in a bimanual task converged to the same performance during practice. Nevertheless, the discovery-learning group demonstrated better transfer results which was considered as evidence to support enhanced exploration.

Pacheco and Newell (2015) measured different patterns of exploration using a range of dependent variables (from dispersion to trial-to-trial structure) to assess the effect of search on transfer. The task used was the virtual throwing in the tablet [the section "Virtual Throwing Task (Pacheco and Newell, 2015)]. The results showed that, first, only trial-to-trial measures of exploration predicted transfer and, second, that maintaining a balanced strategy between exploring and exploiting was the most successful.

The fact that the search patterns *per se* predict the ability to generalize to new situations (in some cases independent of the experimentally imposed practice condition) is intriguing. We speculate that there are some informational variables that are picked up only when given search patterns are employed, allowing individuals to generalize to regions of the task-space never visited. Note that this is/was not dependent on the overall area visited but of the trial-to-trial pattern of search (Pacheco and Newell, 2015). The perception of these informational variables might facilitate what Harlow (1949) described as learning-to-learn: a capacity to generalize to situations that go beyond the current one experienced.

EXPANDING CHANGE AS SEARCHING

In the above sections we provided interpretation of existing positions on learning and speculations as to the role of certain factors in constraining search behavior, as well as how search modifies the workspace. Here we elaborate further on the implications for adjacent areas of skill acquisition if they were to adopt the SSA initiative.

Sports Training and Rehabilitation

It is useful to extend a bridge that shows that our theoretical approach on SSA is applicable to many other domains. It could be said that current sports training and rehabilitation approaches fall victim to the same concerns presented in the section "Traditional Assumptions in Skill Acquisition: Group- and Task-Based Learning." Individuality is regularly discussed and acknowledged among trainers, yet there has not been significant advances to understand the individual nature of change occurring within these intervention programs (Bialosky et al., 2017). The SSA is well positioned in this case to provide therapists and trainers a deeper understanding of the change occurring with their clients and/or athletes.

The parsimonious position holds that principles of rehabilitation, or re-learning are the same as those of learning and development (Newell and Verhoeven, 2017). How the perceptual-motor workspace is constrained by strategies of learning should not be considered unique to healthy normal populations – it can be extended to whole skill continuum (rehabilitation to high performance). Learning occurs as the search for and change of equilibrium regions within the workspace that also satisfy the task demands. Injury or development of a movement disorder can be seen as additional constraints on action possibilities, modifying the search. What remains to be investigated is how specific trauma (e.g., ACL tear, stroke, etc.) would modify the search and search space.

Just as pathology could constrain search, therapy could release constraints. Common manual therapy techniques (e.g., myofascial release) have even been suggested to directly affect both peripheral and spinal mechanisms to improve – for example – joint range of motion and manage recovery and pain (Beardsley and Skarabot, 2015; Kalichman and David, 2017; Monteiro et al., 2017). Thus, it stands to reason that therapists may modulate the properties of the perceptual-motor workspace of the patient, potentially through regulation of muscular tone (Cacciatore et al., 2011a,b; Profeta and Turvey, 2018). Nevertheless, the exact mechanisms of manual therapy are not well established (see Bialosky et al., 2009, 2017).

Recently, the efficacy of contemporary models of training and rehabilitation has been questioned (Stergiou et al., 2006; Schöllhorn et al., 2009; Vaz et al., 2017; Silva et al., 2018). Silva et al. (2018) demonstrate, in comparison to models based on information processing, the utility of ecologically grounded methods of rehabilitation. Also, the role of variability and exploration has been advocated in sports practice (e.g., Orth et al., 2018a,b). These recent advances would be greatly supported by the consideration on the nature of search strategies.

Finally, all interventions can be thought of as a form of practice to induce transfer. Each exercise is done for the express purpose of generalizing the skill learned in one situation to many (e.g., seated leg extensions to locomotion). As we have seen, understanding the search patterns during practice is highly relevant to predict transfer (the section "Exploration of the Task-Space and Transfer") and, in this case, the effectiveness of a training or a rehab program.

Motor Development

As the usage of the term skill acquisition implies, the theoretical and operational aspects presented in earlier sections are all applicable to the study of motor development and, more generally, the construct of change. In this section, we briefly outline a few representative issues that could be fruitfully addressed in motor development with the search strategy approach.

A long-standing question in motor development is whether there is an order to which the individual component variables (joint motions) are frozen or released either individually or in combination (coupled) as a function of development. Gesell (1929) proposed that the developmental order to the effective functioning of the joint space motions (DFs) was anatomically organized in terms of realizing an unfolding directional control: namely, cephalo-caudal, proximal-distal, and ulnar-radial. A competing account holds that is the neural development of the central and peripheral nervous systems that drives the order of engagement of the functioning DFs (McGraw, 1945). Another hypothesis is that the segment masses of the limbs and torso in action are the primary determiners of the unfolding order to children' coordination and control in movement skills (Thelen and Smith, 1994). The systematic manipulation and analysis of the relevant variables, including the task demands (Newell, 1986), could help unravel this still open and basic question on the emergence of the fundamental motor skills (e.g., sitting, standing, reaching). An analysis of the search strategy used to realize performance change in the task-space as a function of the particular motor skill would be foundational finding from a developmental perspective.

An interesting possibility is to see the classic freezing-and-freeing stages of Bernstein (1967) as a process that facilitates search over development. He proposed that, initially, the system would avoid dealing with the complexity of the body by decreasing the number of degrees of freedom to a minimum. In search terms, this would mean that the whole space of possibilities has been decreased to a minimum of dimensions, allowing exploration of the task-space to occur through parameterization only. As relevant informational variables of the task-space had been attended, and as organismic constraints and task goal requires (see Newell and Vaillancourt, 2001), new dimensions are explored, degrees of freedom are freed, and, later, reactive phenomena are exploited. From our results, we can speculate that inherent and external variability allow perception of the most appropriate dimensions to be explored and how to exploit reactive phenomena (Schöllhorn et al., 2009).

Brakke and Pacheco (2019) have already considered search in the motor development domain. In following the lead of Thelen et al. (1993) that detailed how infants explore parameters of movement to facilitate the emergence of reaching, Brakke and Pacheco (2019) mapped the many possible parameters that toddlers could search on to stabilize the performance of the anti-phase pattern in drumming. As in all search studies, they found individual strategies based on different movement parameters (i.e., frequency of oscillation, amplitude ratio between limbs, etc.) that allowed toddlers to break the tendency to perform the in-phase pattern and perform the required pattern.

The fact that one can apply SSA in the motor development domain is not surprising as many authors have highlighted the huge influence of exploratory patterns in development (e.g., Eppler et al., 1996). SSA, differently, is just investigating how these emerge in terms of systematic time-dependent patterns and what are the effects of different exploratory patterns in development. The importance of this study goes beyond showing that SSA can nicely demonstrate how individuals explore the dynamics described in the HKB (and its developments, see de Poel et al., 2009) to acquire a new skill – an example of the integration discussed in the section "Introduction."

CLOSING COMMENTS

In this paper we have drawn on the assumption of learning as searching to examine analytically and experimentally the multiple processes of change that emerge in perceptual-motor skills through practice. Our approach to search strategies continues to build within tenets of the ecological theory of perception and action (Turvey, 1992; Warren, 2006; Profeta and Turvey, 2018) and in particular the original framework of search processes and the perceptual-motor workspace (Kugler and Turvey, 1987; Newell et al., 1989). A distinctive emphasis here, however, is on individual analysis of the change in performance and its expressions in the different behavioral frames of reference (Saltzman and Kelso, 1987; Newell and Liu, 2014): namely, goal, task, perceptual-motor workspace, and individual component DFs.

We have provided evidence for the central proposition on the nature of search strategies locating and creating stable equilibrium regions in the perceptual-motor workspace and how these strategies relate to the emergent movement forms in the acquisition of coordination, control, and skill. In this regard we have brought together the role of intrinsic dynamics (Kelso, 1995) and the emergence of processes of search in task space that can be independent of the gradient descent properties of the landscape of both task and intrinsic dynamics (Newell et al., 1989). This possibility opens the question on the processes of perception of informational variables that grasp macroscopic properties from task and perceptual-motor workspace that leads to divergent search patterns (e.g., Jacobs et al., 2011; Michaels et al., 2017). It also opens the question as to the learner's priorities for using information on one level or another in the search process for learning.

In both discrete and continuous perceptual-motor skills we have shown that a search strategy analysis reveals new aspects about change and learning beyond those from the traditions of task-based assumptions and averaged performance outcome over time. Through the search process, individuals adapt to the pick-up of task relevant perceptual variables and change their movement form according to the stability of the performed action and its outcome in relation to the task demands. Contemporary experimental findings have revealed some clues as to how the search process occurs given the interaction of individual intrinsic dynamics in the context of task requirements by extracting the commonalities arising from the individual differences in practice. Also, we elucidated and evaluated potential principles that drive the change – e.g., exploitation of more tolerant task-space solutions, emergence of compensatory mechanisms, and inherent variability. One might recognize that the potential benefits of degeneracy of the system for the learner become the potential challenge for the researcher.

Examining search behavior at goal, task, and perceptual-motor workspace adds to this challenge of seeking order in the time-dependent processes across variables – the search behavior. All these challenges and questions can be approached from the contemporary developments in search processes for the learning of perceptual motor skills.

DATA AVAILABILITY

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

MP, CL, and KN derived the idea, and wrote and revised the manuscript.

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CONCEPTUAL ANALYSIS
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How Radical Is Embodied Creativity? Implications of 4E Approaches for Creativity Research and Teaching

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Modern ideas of embodiment have been influential in cognitive science for the past several decades, yet there is minimal evidence of embodied cognition approaches in creativity research or pedagogical practices for teaching creativity skills. With creativity research in crisis due to conceptual, methodological, and theoretical issues, radical embodied cognitive science (RECS) may offer a framework to move the field forward. This conceptual analysis examines the current state of creativity research from the 4E (embodied, embedded, enactive, and extended) cognition and RECS perspectives. Two streams are critiqued for their potential to further knowledge about the development of creative expertise and inform educational practices. Promising directions for future research is discussed, including ways dynamical systems approaches, such as those used in improvisational and musical creativity, might yield new insights about how people develop creative expertise and help address the "higher order thinking" criticisms of RECS.

Keywords: embodied cognition, embodied creativity, embodied design, 4E creativity, enactive cognition, distributed cognition, social creativity, embodied metaphors

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INTRODUCTION

Modern ideas of embodiment can be traced back several decades (Brooks, 1991; Varela et al., 1991; Lakoff and Johnson, 1999), and the notion that cognition may be "radically" embodied has been at the forefront of cognitive science debate since the early 21st century (Thompson and Varela, 2001; Chemero, 2009). Radical embodied cognitive science (RECS) proposes that *cognition is for action*, and thus is best understood in terms of person-environment dynamics, an alternative to computational cognition (CC) models describing rule-based information processing and manipulation of abstract mental representations (Chemero, 2009, pp. 28–44). Importantly, the RECS perspective suggests that how we learn and develop expertise is shaped, constrained, and enacted through exploration and interaction with our physical environment. Despite the potential for RECS to yield new insights into how people acquire creative abilities, the field of creativity research has not given much attention to the role of the body or its physical context (Glăveanu, 2014b; Malinin, 2016). Given that creative process research has made little progress in recent years (Fryer, 2012; Glăveanu, 2014a) and continues to suffer from lack of relevance for informing educational practices or learning environments (Plucker et al., 2004; Barbot et al., 2015), researchers may benefit from adopting an action-oriented and physically-situated perspective. This paper examines the current state of creativity research with respect to embodiment theories in order to focus scholarly discussion around the potential for an embodied perspective to help address conceptual, methodological, and theoretical barriers limiting practical application in educational settings.

As a research area within cognitive science, embodied cognition (EC) is an interdisciplinary effort with diverse and sometimes conflicting perspectives (Gallagher, 2015a). Generally speaking, there are key commonalities among the many existing theories. Foremost is that the body plays a role in shaping perception and cognition. To what extent remains debated. Theories grounded in philosophical perspectives (e.g., Husserl, Merleau-Ponty, and Heidegger) typically focus on ways the body constrains cognition (Borghi and Cimatti, 2010) whereas RECS, with concepts traced back to Gibson's (1979) ecological theory of perception, is concerned with how cognition is enacted through, or partially constituted by, bodily and environmental processes (Chemero, 2009, pp. 17–44). The second commonality is rejection of the computational "classical sandwich" (Hurley, 2002, p. 401) model of the mind, which describes cognition as staged information processing: perception, then cognition, and finally action. The embodied approach theorizes a complementary relationship between action and perception, and is concerned with how action influences perception and cognition. RECS takes this idea further, arguing that cognition is best understood as a dynamical system encompassing brain, body, and world (Thompson and Varela, 2001, p. 418). Central to RECS is that cognition is not wholly in-the-head, but also involves the body and aspects of the environment. The core conceptual issue between EC and RECS theories concerns whether they complement or oppose the classical computational theory of mind (Gallagher, 2015a). Thusly, a major criticism of RECS is that it may not be sufficient to describe higher-order thinking without relying to some degree on mental representation (Chemero, 2009, p. 43).

Higher-order thinking is a concept based on learning taxonomies, which are used by educators to describe learning behaviors and distinguish levels of cognition. The well-known Bloom's Taxonomy was revised in 2001 to describe creativity as the most complex (highest-order) process in the knowledge hierarchy (Anderson et al., 2001). Not long after, the Partnership for 21st Century Learning identified four learning skills and competencies essential for a knowledge economy: creativity, collaboration, communication, and critical thinking (4Cs). Researchers generally agree that creativity involves a unique combination of ordinary cognitive processes, such as divergent and convergent thinking, conceptual combination (analogical and metaphorical thinking), mental imagery, and analogical reasoning (Ward and Saunders, 2003; Runco, 2007b). It is also understood to be a teachable skill (Scott et al., 2004; Ward and Kolomyts, 2010), however, specific pedagogical practices that lead to creativity have not been identified (Sawyer, 2018). Everyone has capacity to be creative; although professional and extraordinary levels of creative achievement also require sufficient intelligence and domain knowledge (Sternberg and O'Hara, 1999; Jauk et al., 2013). How people actually develop creative expertise is still not well-understood, which may be due, in part, to issues with how creativity is defined and measured and the ways research areas are siloed.

Dietrich (2007), Glăveanu (2014b), and others have proclaimed that the field of creativity research is "in crisis" because of conceptual, methodological, and theoretical issues. First, the commonly accepted definition of creativity – as the ability to produce something novel (or original or unique) and useful (or valuable or meaningful) – does not sufficiently describe the concept's multidimensionality (Dietrich, 2007; Fryer, 2012; Glăveanu, 2014b; Barbot et al., 2015). It limits attention to personal attributes and products produced, neglecting the physically and socially situated processes of problem finding and solving. Second, creative process research has shifted from a focus on identifying and modeling stages of creativity (for example, Wallas's (1926) four-stage model) to mainly experimental studies of divergent thinking productivity (Dietrich, 2007; Glăveanu, 2014a; Barbot et al., 2015). The tendency to consider creativity an "intra-psychological activity" (Glăveanu, 2014b, p. 18) focuses on the outcome of creative thought as if cognition occurs in a vacuum devoid of bodily activity, material environment, and social-cultural context. Finally, creativity research is generally organized according the 4P's: person; process; product; or press, social and/or physical contexts (Rhodes, 1961). Recently scholars have argued that this categorization is not sufficient to describe the field (Runco, 2007a; Lubart, 2017) and has enabled a disjointed understanding of creativity (Glăveanu, 2013). Although useful when creativity research was in its infancy, lack of significant progress in the creative process stream suggests 4P categorizations may be creating artificial barriers limiting scientific progress. New approaches are warranted that more deeply consider relationships between the 4Ps. EC and RECS perspectives may provide a framework that will move the field forward toward developing a new theoretical model better explaining the development of creative expertise and more useful for informing educational practices in formal and informal learning environments.

A CONCEPTUAL ANALYSIS OF RADICAL EMBODIMENT IN CREATIVITY

The concept of RECS is often described in terms of **4E** (***embodied, embedded, enactive, extended***) cognition, explaining ways the mind is not solely located in the brain but also involves the body and the body's situation in the environment (Menary, 2010b; Newen et al., 2018). Although each of the E's offers a different perspective on the nature of cognition, they are not entirely discrete; principles often overlap between them. ***Embodiment*** refers to how the body contributes to cognitive process and is based on the premise that the brain and body evolved together and are therefore intrinsically coupled. It considers the brain as part of a larger cognitive system, including the body's nervous system and sensorimotor capabilities (Gallagher, 2015b), suggesting separation of body and brain is artificial. Gallagher (2015b) explains how body schema, a sensory-motor system that functions without explicit awareness (p. 24), structures our interactions in the world, shaping the mind at a fundamental level

(p. 141). He suggests that once we understand how body schema shapes perception, we will uncover how it also shapes cognition as a whole, because perception is fundamental to cognition (p. 137). By this account, even abstract concepts are shaped by body schema. Lakoff and Johnson (1980, 1999) suggest we use linguistic metaphors to link abstract concepts with concrete, bodily experiences (such as "feeling warmth" to express affection). An embodied approach in creativity research might explore how, for example, gestures and postures influence perception during ideational processes. In his study of over 100 eminently creative people from diverse fields, Csikszentmihalyi (1996) found they often engage in common habits involving similar gestures or postures to support particular creative processes and "give their surroundings a personal pattern that echoes the rhythm of their thoughts and habits" (p. 127). Embodied creativity research might lend empirical insights into anecdotal creative habits.

Embedded cognition describes coupling with environments (physical and socio-cultural), which shape, and are shaped by, the actors who inhabit them. This concept is inspired by Gibson's (1977, 1979) ecological theory describing perception as direct (i.e., not requiring mental representation) and suggests actors perceive their environments in terms of affordances (opportunities for action) they provide to them. Affordances thus depend upon the unique bodily capabilities of the actor. Suchman (1987, 2007) and Hutchins (1995) extended these concepts to socio-cultural environments. Suchman (2007) studied human-machine interactions, realizing a photocopier help system's communications breakdown was because its designer misunderstood the nature of action. She proposed a shift in the way plans are conceptualized, from "cognitive control structures that universally precede and determine actions to cultural resources produced and used within the course of certain forms of human activity" (p. 13). Planning, she explained, unfolds through a people's interactions in their environments, as *discursive practice*. Hutchins studied a naval navigation team, concluding that cognition is a culturally constituted activity that depends upon the unfolding situation in which it occurs. He found that people off-load cognitive effort to their environments (through artifacts and other people) and establish dynamic social structures to improve cognitive load-balancing. More recently, Ingold's (2002, 2010, 2013) study of artisans found their "craft" is not (solely) bodily skill, but emerges in a system of relationships and interactions situated in a particular socio-material environment. Embedded cognition approaches, such as Ingold's, may yield new insights into the development of creative expertise acquired through situated practice.

Enactive cognition argues that cognition is for action; through meaningful actions we make sense of our environment, allowing us to maintain our existence within it (Varela et al., 1974; Varela et al., 1991; Thompson and Stapleton, 2009). The enactive thesis, as developed by Varela et al. (1974, 1991), is influenced by *autopoiesis*, a concept that describes how organisms create their own experiences by initiating actions in environments. The enactive perspective considers people as "autonomous systems" who "regulate their interactions with the world in such a way that they transform the world into a place of salience, meaning, and value" (Thompson and Stapleton, 2009, p. 25). This idea aligns with how people often describe creative experience. For example, the architect Olga Aleksakova discusses thinking-in-action while cutting a foam block to create the design for a building (Yaneva, 2009). She explains how she began without a preconceived notion of the final form, rather it emerged though the intertwined processes of acting and perceiving. Each cut revealed to her new opportunities for subsequent actions to make the block more "beautiful." Her creative process was an adaptive, reciprocal exchange between creator and creation. Examples like this one, suggest that creative expertise is developed through situated practice. Creative professionals develop a repertoire of actions as part of their practice, using them to initiate and sustain improvisational and adaptive interactions toward finding meaning in a creative situation.

Finally, ***extended cognition*** claims that thinking is distributed beyond the body (Clark and Chalmers, 1998, 2008). The things in our environment are incorporated into our cognitive systems, similar to the neuronal processes in the brain. This "first wave" extended cognition is committed to the *parity principle*, which argues that if non-biological agents extend cognition in a way that is functionally equivalent to intracranial processes, then that part of the world is part of the cognitive process (Clark and Chalmers, 1998, p. 8; Menary, 2010a) Clark (2008) uses an exchange between Richard Feynman and Charles Weiner to illustrate this concept. Feynman explains to Weiner that his notebook was not a *record* of his thinking, because his thinking happened outside of his head with pen and paper – the notebook *was part of* his thinking. "Second wave" extended cognition is focused on cognitive integration, explaining how bodily (internal) and non-bodily (external) aspects of cognition are integrated to form something new (Menary, 2010a). This wave does not rely on the parity principle, instead taking embodied-embedded cognition as a starting point. "Third wave" extended cognition proposes that cognitive integration is reciprocal, dynamic, and ongoing (Sutton, 2010). The boundaries of the mind are flexible and open-ended; cognitive processes unfold over time, involving the body, other people, and resources in the environment, shaped by socio-cultural practices. Significantly, the extended cognition approach argues that too much emphasis on neuronal and bodily aspects of cognition can obscure the importance of dynamic relationships between agent and artifacts. Of the 4Es, extended cognition is the most controversial, however it suggests that artifacts play a more significant role in creative cognition than typically considered in the literature. This has implications not only for how creativity is taught, but also for the design of learning spaces and other settings intended to support creativity.

Chemero (2009) frames RECS as a "variety of extended cognitive science" (pp. 31–32). He distinguishes RECS from Clark's extended mind theory by its focus on a dynamical and non-linear coupled perspective, rejecting the "wide computationalism" and representational (linear) coupling that is typically the target of anti-extended-mind arguments. Baggs and Chemero (2018) also advocate for a "productive synthesis" between competing (and, he argues, complementary) ecological and enactive RECS approaches. The ecological perspective studies the environment in terms of opportunities (affordances) or constraints it offers for actors. The enactivist perspective, with its constructivist grounding, begins with the actor and is concerned by how it constitutes its own unique *umwelt*[1]. They suggest three definitions to clarify what is meant by "environment" in order to synthesize these perspectives. First the *physical world* describes the enduring structure of the environment irrespective of species inhabiting it. Second, *habit* describes the species-specific environment. Finally, *umwelt* describes the actor-specific environment. For the purpose of this conceptual analysis, the current state of embodied creativity research will be analyzed with respect to the 4Es from a synthetic RECS perspective as suggested by Chemero. Environment will be used as an umbrella term to describe both human-specific environment (habitat) and actor-specific environment (umwelt).

How people believe their bodies, artifacts, and environments shape creative processes is evident in personal accounts of creativity throughout history (Malinin, 2016), yet embodied creativity is a newly emerging research area, generally organized into two streams. The first stream involves experimental examination of embodied metaphors associated with creative thinking. These studies typically assess effects on ideational productivity of enacting metaphors through specific bodily movements. For example, free walking might enact the embodied metaphor *thinking outside of the box* (Leung et al., 2012; Kuo and Yeh, 2016). The second stream examines creativity from a dynamical systems perspective as an emergent phenomenon that is distributed between people and artifacts of the material environment. For example, musical creativity is examined as a system of emergent, dynamic interactions among musicians and instruments (Walton et al., 2014, 2015; Schiavio and Van der Schyff, 2018; van der Schyff et al., 2018) There are several key issues distinguishing these two approaches. First, the creative metaphor stream is concerned with understanding creative potential of the general population (typically college students). System approaches are often used to understand creative expertise by studying professionally or historically creative people. Second, the creative metaphor approach equates creativity with divergent or convergent thinking productivity, which are typically measured through Alternative Uses Test (AUT)[2] or Remote Associates Test (RAT).[3] The systems approach is concerned with the entire creative process, beginning with problem finding/framing through implementation. Where the embodied metaphor stream generally employs quantitative methods, the systems approach is more often qualitative or mixed methods — for example, integrating observation, sensors, and interviews to understand the dynamic interplay between people and artifacts with respect to creative processes. For the purpose of this conceptual analysis, creativity is defined as an iterative process that involves (a) identifying a problem or area of concern; (b) generating, testing, and elaborating on ideas toward developing a product (e.g., artifact, theory, methodology, system, performance, etc.); and (c) implementation and evaluation by others (for example, users and experts in the field). Divergent and convergent thinking are considered here as sub-processes, occurring throughout problem finding, generation/elaboration, and implementation.

Embodied Metaphorical Creativity

Lakoff and Johnson (1980) proposed that mental concepts, such as metaphors, are directly tied to bodily experiences, suggesting a radical break with CC paradigms. Metaphors operate as mappings between source concepts, grounded in literal meanings (i.e., concrete, physical contexts), and abstract ideas. Embodied metaphors describe how literal and abstract meanings become intertwined, such that abstract concepts are metaphorically grounded in sensorimotor experiences. As embodied cognitive science has matured, some scholars argue that the embodied metaphor thesis is not radical, rather it is an example of grounded cognition that is compatible with CC models (Adams, 2010; Gallagher, 2015a; Shapiro, 2019). Nonetheless, a number of experimental studies examining embodiment in creativity have focused on how movement might enact embodied metaphors to enhance divergent and convergent thinking (Stanciu, 2015; Frith et al., 2019).

Many metaphors describe aspects of creative thinking, such as THINKING OUTSIDE OF THE BOX (Leung et al., 2012; Kuo and Yeh, 2016), BREAKING THE WALLS, THINKING FLUIDLY (Slepian and Ambady, 2012), MOVING FORWARD (Oppezzo and Schwartz, 2014), ON THE OTHER HAND (Leung et al., 2012), PUTTING TWO AND TWO TOGETHER (Leung et al., 2012), SQUEEZE YOUR HEAD (Kim, 2015), BEING OPEN (Hao et al., 2014, 2017; Andolfi et al., 2017), and BEING WARM OR COOL (Ijzerman et al., 2014). Two recent reviews found that, despite the small number of studies, embodied creativity metaphors did enhance divergent and convergent ideation, typically measured through AUT and RAT instruments (Stanciu, 2015; Frith et al., 2019). However, these experimental studies typically suffer from small sample sizes and lack of replication (see summery, **Table 1**). Studies examined how walking versus sitting (Leung et al., 2012; Oppezzo and Schwartz, 2014; Kuo and Yeh, 2016), arm movements/gestures (Leung et al., 2012; Slepian and Ambady, 2012; Kim, 2015; Wang et al., 2018), posture (Hao et al., 2014, 2017; Andolfi et al., 2017) and temperature (Ijzerman et al., 2014) might enact embodied metaphors immediately before or while engaging in creativity tasks.

Walking is a common habit people employ to help them come up with new insights when working on creative problems (Ghiselin, 1954; Buttimer, 1983; Solnit, 2001; Malinin, 2016). It has long held a special place in creativity; Aristotle's Peripatetic School was so named because he walked with his students while philosophizing (Solnit, 2001). Walking has been used to enact metaphors for creative thinking, including THINKING OUTSIDE THE BOX, BREAKING THE WALLS, and MOVING FORWARD. Leung et al. (2012) found participants who engaged in creativity tasks while free-walking outside of a (5′ × 5′)

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[1] von Uexküll (1926/2010) described *umwelt* as the "surrounding environment" of an organism that is structured through its senses and abilities. Every organism has its own umwelt, even if they occupy the same space. The living organism is always at the center of its umwelt and is conceptually bound to it.

[2] AUT measures divergent thinking (fluency, originality, flexibility, and elaboration of ideas) by coming up with alternative uses for common household objects, such as a brick.

[3] RAT measures convergent thinking by identifying a single word that links together a list of three common stimulus words that are seemingly unrelated. For example, "box" links the stimulus words "square," "cardboard," and "open."

TABLE 1 | Embodied metaphorical creativity studies.

Metaphor	Enacting bodily experience	Enhanced creative thinking	Sample	Authors
Thinking outside the box	Free-walking	Divergent (originality)	102 college students	Leung et al., 2012
	Free-walking	Divergent (originality, fluency, flexibility)	64 college students; 32 adults aged 65 +	Kuo and Yeh, 2016
	Virtual free-walking	Divergent (originality)	73 university students	Leung et al., 2012
Moving forward	Treadmill walking	Divergent (originality. fluency); convergent analogy creation	48 college students	Oppezzo and Schwartz, 2014
Breaking the wall	"Breaking" arm movement	Divergent (originality, fluency, flexibility)	41 college students	Wang et al., 2018
On the other hand	Switching raised arms	Divergent (originality, fluency, flexibility)	40 college students	Leung et al., 2012
Putting 2 + 2 together	Moving arms together	Convergent thinking	64 college students	Leung et al., 2012
Thinking fluidly	Fluid arm movements	Divergent (fluency, originality, flexibility); convergent (remotely associations)	College students: 30 divergent; 150 converg.	Slepian and Ambady, 2012
Squeeze your head	Squeezing soft ball	Divergent thinking (originality, fluency, flexibility)	50 college students	Kim, 2015
	Squeezing hard ball	Convergent thinking	32 college students	Kim, 2015
Being open	Open body posture sitting	Divergent (originality, fluency, flexibility)	102 college students	Andolfi et al., 2017
	Open posture, positive emotion, standing	Divergent (originality) and associative flexibility	149 college students	Hao et al., 2017
	Seated with arm flexion, palm facing body	Divergent (originality and fluency)	100 college students	Hao et al., 2014
	Lying with arm extension, palm facing body	Divergent (originality and fluency)	100 college students	Hao et al., 2014
Being warm/cool	Warm environment	Divergent (fluency)	60 children aged 4–6	Ijzerman et al., 2014
	Cool thermal pad	Reacted faster to metaphorical statements, more abstract ideas	27 college students	Ijzerman et al., 2014
	Warm thermal pad	Higher quality, realistic ideas	33 college students	Ijzerman et al., 2014
	Holding warm cup	Relational thinking	23 college students	Ijzerman et al., 2014
	Holding cool cup	Divergent (originality)	33 college students	Ijzerman et al., 2014

box had better scores on both divergent (originality) and convergent thinking tasks than when sitting inside the box during tasks. Similarly, Kuo and Yeh (2016) found free-walking benefited ideational originality, fluency, and flexibility over rectangular (box-shaped) walking patterns for young and older adults. Virtual-reality (imagined) walking was also found beneficial. Participants whose avatars free-walked generated more original responses than those with avatars walking in rectangular patterns (Leung et al., 2012). In a study examining, BEAKING THE WALLS, participants used a game controller to move along a zigzagged corridor, turning their bodies to change direction (Wang et al., 2018). A wall appeared blocking the corridor in the "break" condition and participants destroyed it with the game controller in order to proceed. The "break" condition benefited ideational originality, fluency, flexibility, and persistence. Oppezzo and Schwartz (2014) hypothesized walking would benefit divergent thinking by helping participants MOVE FORWARD from one idea to the next. Walking on a treadmill facing a blank wall improved originality and fluency over sitting, but slightly reduced RAT scores of convergent thinking during and after walking. Free-walking outdoors and treadmill walking similarly benefited creative analogy generation, however walking outdoors contributed to more novel analogies, perhaps due to the additional sensory stimulation. In general, embodied metaphor studies demonstrate walking, particularly free-walking, improves divergent thinking but may slightly harm performance on memory intensive convergent thinking tasks.

Gestures, using arms and hands, were examined in a few studies of creativity metaphors. In an experiment examining ON THE OTHER HAND participants held one arm forward with palm up while completing creativity tasks (Leung et al., 2012). Switching hands improved ideational fluency, flexibility, and originality compared to putting the same hand forward in both trials. The metaphor PUTTING TWO AND TWO TOGETHER was enacted through an activity where participants moved stacks of coaster-halves located on the left and rights side of the table to the middle or simultaneously assembled the halves into a single stack (Leung et al., 2012). Combined stacking benefited convergent thinking whereas divergent thinking (fluency, flexibility, and originality) did not significantly different between conditions. Slepian and Ambady (2012) had participants trace two different drawings, one to elicit fluid arm movements (using curved lines) to enact THINKING FLUIDLY and one to create zigzagged movements (using straight lines and angles). Participants in the fluid condition showed improved fluency, originality, flexibility, and better connected remotely associated concepts. Analytical (convergent) thinking results did not differ between conditions. Kim (2015) examined a metaphor commonly used in Korea for fluid, divergent thinking, SQUEEZE YOUR HEAD. Squeezing a soft ball during TTCT and RAT assessments improved divergent thinking overall, and specifically fluency, flexibility, and originality. Squeezing a hard ball benefited convergent thinking. Interestingly, the participants for this study were British, where the metaphor is not commonly used. This might suggest a relationship between enacting a squeezing motor response and creative thinking. Or there may be another explanation. For example, Goldstein et al. (2010) had participants squeeze a ball with the left hand to artificially activate the right hemisphere prior to completing RAT, which improved performance.

Posture has been the focus of several studies examining, BEING OPEN. Andolfi et al. (2017) had participants sit in either an approach/expansive (with legs slightly spread and hands resting on legs) or avoidance/contractive (closed legs with arms crossed) posture while completing a series of divergent thinking tasks. Higher scores for fluency, flexibility, and originality were associated with the open posture. There was no significant difference for non-creative tasks or comfort between the two postures. Hao et al. (2017) had participants stand for their experiments examining relationships between posture, emotion, and creativity. Participants first watched videos to induce positive or negative emotions and then they completed AUT problems in either an expansive or contractive posture. In the open posture, participants stood with weight shifted to the front leg, arms down and hands slightly spread. In the closed position they stood with arms and legs crossed. Higher originality scores were associated when emotion and posture were compatible (positive-open or negative-closed). Participants also had greater associative flexibility in the positive-open condition and higher persistence in negative-closed conditions. In a prior study Hao et al. (2014) examined interactions between body and arm posture to enact approach or avoidance embodiment. They compared arm extension and arm flexion in seated and lying postures. They founded being seated with arm flexion was associated with higher AUT fluency and originality whereas when lying down the converse was true. In the seated condition, the arm was flexed with palm facing toward the participant. In the lying posture, the arm was flexed with palm upward, facing away from the participant, but in the arm extended position the palm was downward, facing toward the participant. Proximity between palm and body seemed to enact an approach motor action, found in prior research to improve global processing, abstract thinking, and making connections between remote concepts (Andolfi et al., 2017).

Environmental conditions may also enact embodied metaphors (Jia et al., 2009; Ijzerman et al., 2014). People commonly believe certain places help them be more creative (Kristensen, 2004; Vohs et al., 2013; Malinin, 2016) and there is some evidence that atmospheric conditions alone can elicit embodied metaphors benefiting creativity. Ijzerman et al. (2014) explored how temperature might elicit BEING WARM (relational thinking) or BEING COOL (conceptual distance) in a series of three experiments. The first study used environmental temperature, conducting studies with children in rooms that were cool (15–19°C/59–66° F) and warm (21–26°C/70–80° F). Children created more fluent drawings in the warm room. In their second study, they used thermal pads to heat or cool adult participants for 3 min prior to completing creative tasks. Participants in the cool condition reacted faster to metaphorical statements during a computer task measuring how fast they switch their interpretive frame. There was no reaction time difference for factual statements between conditions. Therapeutic pads were also used during tasks where participants came up with gift ideas for friends and strangers. In the warm condition, participants developed higher quality, realistic gift ideas for both friends and strangers. In the cool condition, gift ideas were more abstract. In another experiment, the researchers had participants hold a cup filled with a warm or cool beverage while completing a category inclusion task and while coming up with creative names for a new pasta. When holding the warm cup, participants demonstrated more inclusive categorization whereas holding the cool cop benefited originality. These series of experiments suggest environmental warmth may benefit fluidity and relational thinking during creativity whereas cooler temperatures may be useful to elicit more abstract, original thinking.

There does seem to be a small but compelling body of research suggesting the role of the body in enacting metaphors for creative thinking, however more research is needed that replicate results. Nonetheless, these findings align with "traditional" psychology studies demonstrating, for example, benefits of physical activity, including walking (Colzato et al., 2013; Oppezzo and Schwartz, 2014), how movements can activate the right hemisphere to enhance divergent thinking (Goldstein et al., 2010; Mihov et al., 2010), and how the ambient conditions in a setting can benefit creativity through processing disfluency (low level distraction) (Mehta et al., 2012). The embodied metaphor stream underscores how the body constrains cognition, however this is not necessarily incompatible with representational models of cognition. RECS suggests that through movement, such as gesture, the body is able to express abstract concepts without the need for mediating verbal representation (Slepian and Ambady, 2012). The embodied metaphor studies, however, generally focused on ways the body might bias abstract thinking or *mindset* (disposition/intent toward a creative situation) to improve divergent or convergent thinking. This aligns with what Gallagher (2015b) refers to as *minimal embodiment*. Yet there is still potential for advances in this research stream to inform learning space designs and pedagogical practices that consider impacts of environmental qualities, movement, posture, and gesture on different creative processes, including divergent and convergent thinking and conceptual combination (analogical/metaphorical thinking).

Metaphorical thinking is understood to be central to creativity (Kazmierczak, 2003), yet embodied metaphor studies have not attempted to enact metaphors to influence creative insight on ill-defined problems. This is an important area that might inform pedagogical practices to enhance creativity. For example, there are numerous anecdotes suggesting conceptual combination leading to insight is often immediately preceded by embodied, sensorimotor experience. Philo Farnsworth had the idea to project moving images line-by-line while he was plowing a field, leading to the invention of television (Thomas, 2004). George de Mestral was picking burrs off of his dog when came up with the inspiration for Velcro (Hargroves and Smith, 2006). There is an untapped potential for experimental studies of embodied metaphor to examine how sensorimotor experiences might *constitute* new knowledge leading to creative breakthough. The experimental work of Slepian and Ambady (2014) creating novel embodied metaphors could provide a direction for future research –and would align more closely with the RECS approach. The pair taught participants novel metaphors pertaining to weight and time and found these influenced estimates of physical weight (when holding a book), suggesting embodied simulation. Metaphors did not influence weight perceptions when looking at photos of books, suggesting results were not because of semantic association. Studies examining novel metaphor creation during authentic problem solving might provide greater insight into the role of sensorimotor experience in enacting new insights. This could help to answer the question of whether creativity requires internal representations or if creativity is distributed beyond the brain, to include the body and environment.

Creativity-in-the-Wild

A core argument of RECS is that human cognition is situated activity, characterized as a dynamical system encompassing brain, body, and world. Dynamical systems approaches employ "mathematical abstraction that unambiguously describes how the state of some system evolves over time" (Beer, 2014, p. 134). It includes states, time, and operators that transform a state at one time to another state at a different time. This is an alternative to experimental embodied-metaphor approaches that focus attention to the role of action in ideation processes, but do little to dispel the notion that creativity happens *solely in the head*. Since the 1970s, cognitivist approaches, which imply creativity starts with a mental idea subsequently imposed upon a material world, have supplanted empirical study of physically-situated, dynamic practices, such as tool use during creativity (Baber, 2019). A notable exception, Schön (1983) observed architects and others in their workplaces, finding that people *think-in-action*, by "conversing" with the materials of a creative situation (p. 175). Csikszentmihalyi (1990) interviewed over 100 creative professionals who described a similar process, which he called *flow*. Tools, materials, and settings are critical for initiating and sustaining a flow state – which is when people feel most creative (for example, pp. 54–58 and p. 120). Woodman and Schoenfeldt (1990, p. 10) argued decades ago that to understand creative behavior, one must begin by understanding the "organism-in-its-environment." There are a few recent efforts incorporating dynamic systems theory (DST) in studies of performing arts and design, yet domain general studies remain rare – despite evidence that creativity unfolds through person-environment interactions with tools, materials, and even workplace settings during creative processes (Sennett, 2008; Pallasmaa, 2010; Ingold, 2013; Malafouris, 2013; Glăveanu, 2014a).

Complex-systems theories of creativity emerged in the 1980s, acknowledging creativity as a socially situated process. Psychological studies recognized that people work within particular social structures, which influences creativity (Amabile, 1983, 1996) and creative products are evaluated by members of a person's field through consensual assessment (Feldman et al., 1994). The material environment remains mostly disregarded. Amabile (1998) argued the physical workplace setting does not play any significant role in creativity. Csikszentmihalyi (1996, p. 135) suggested the material environment is important for creativity, but it may be impossible to empirically explain how it might catalyze creative processes. Developments in 4E cognition have informed complex systems frameworks for two recent studies of embodied creativity. Both examined the materiality of creative practices compared across domains of visual and performing arts, design, writing, and science. First, Glăveanu et al. (2013) proposed an action framework based on Dewey's (1934) experiential learning theory to guide qualitative analysis of interviews conducted with 60 artists, musicians, designers, writers, and scientists. They propose that creative acts typically begin with an impulse, which varies by domain (e.g., to express, to solve a problem, etc.). Material and methodological constraints on creative acts constitute experiences through which the creator gains awareness until eventually achieving emotional fulfillment and professional satisfaction. Malinin (2016) included the architectural environment in her analysis of accounts by creative professionals for evidence of embedded, embodied, and enactive cognition. The resulting theoretical framework, grounded in Gibson's (1977) affordance theory, describes how creative niche construction (*umwelt*) is constituted through person-environment coupling. She found creatives habitually exploit features and qualities of their material environments to engender, sustain, and curtail different modes of creativity, enhancing creative productivity. The materiality of creative practices across domains is apparent in both studies of creativity *in situ*, suggesting it may be time to finally leave behind purely mental models that focus on divergent and convergent thinking in favor of DST approaches. Furthermore, the theoretical frameworks developed from these studies suggest that person-material-environment interactions – doing-and-undergoing (Glăveanu et al., 2013) or perceiving-in-action (Malinin, 2016) – constitute transformative creative experiences.

The idea that creativity is *emergent* and *distributed* between people and artifacts is not a new concept in improvisational performing arts, such as comedy theater (Sawyer, 1999; Sawyer and DeZutter, 2009), music (Walton et al., 2014, 2015, 2018; Schiavio and Van der Schyff, 2018; van der Schyff et al., 2018), or partner-dance (Kimmel et al., 2018; McClure, 2018). Sawyer's (1999) seminal study of theatrical improvisational was informed by Hutchins's (1995) theory of distributed cognition. Hutchins argued that the best way to understand embodied activity is to study real world processes by observing people in their workplaces. Through this methodology he illustrated how real-world problem solving, which he called "cognition-in-the-wild," is distributed between people and artifacts. Improvisational creativity is unique; the process *is* the creative product and activities are interactional and unpredictable (Sawyer and DeZutter, 2009). Temporal, observational studies of improvisational performances reveal some common principles about person-environment interactions during this type of creativity:

- Creative synergies emerge without prior planning or scripting and cannot be attributed to the intentions or actions of any particular participant (Sawyer and DeZutter, 2009; Kimmel et al., 2018).
- There is moment-to-moment contingency where each action depends on the one just prior and any action can

be changed by subsequent actions (Sawyer and DeZutter, 2009; van der Schyff et al., 2018).

- Cultivation of embodied perception — acquired through a repertoire of bits/motifs (relatively stable interactional routines) — increases potential for novelty (Sawyer and DeZutter, 2009; Kimmel et al., 2018; McClure, 2018).
- Interactions constitute micro-affordances, which enact meaning for participants (Sawyer and DeZutter, 2009; Kimmel et al., 2018).
- Creativity is a complex system constrained by interactions (Sawyer and DeZutter, 2009); constraint lies in the structure of the partnership (Walton et al., 2015; McClure, 2018; van der Schyff et al., 2018) and the setting (van der Schyff et al., 2018; Walton et al., 2018).
- Higher level structures emerge, exhibiting global system behavior (Sawyer and DeZutter, 2009); the creative group becomes so tightly coordinated that they behave as a single entity and not a collection of individuals (Walton et al., 2014, 2015).
- Social and material interactions are reciprocal; the creative process is transformative (Glăveanu et al., 2013; van der Schyff et al., 2018).

Design creativity has also been examined as a type of improvisational performance between actor and materials of a creative situation (Schön, 1983; Pereira and Tschimmel, 2012; Choi and DiPaola, 2013; Rietveld and Brouwers, 2017; Baber et al., 2019). Baber et al. (2019) used a RECS framework to study jewelry design. They analyzed data from interviews, motion capture, and sensors fitted to tools to understand how artifacts (tools, equipment, materials, and workplace) shape creative activity, finding jewelry design involves more technological reasoning than abstract reasoning. They propose that (a) creativity is a physical act where action and perception are intertwined, (b) creativity emerges through incremental insight as responses to changing situational cues, (c) it involves a repertoire of responses to situational cues and constraints, and (d) constraints are necessary, but too many inhibit creativity. Like research on improvisational arts, their study demonstrates how creativity is emergent and distributed between actor and artifacts. Pereira and Tschimmel (2012) also found jewelry making to be an emergent phenomenon. They suggest perception is at the core of creativity, which might emerge through *confused perception* (such as Beethoven's deafness), *malfunctioning perception* (such as with mental illness), and *intentional perception*, developed through expertise and use of strategies like associative and analogical thinking. Rietveld and Brouwers (2017), in their ethnography of architectural practice, noted that architects also continually shift perspectives to perceive new affordances in a creative situation. Some ways this is done in both jewelry making and architecture include ideation drawing and tool use.

Baber et al. (2019) propose that designers *instantiate events* by creating ideation sketches. Chemero (2000), Chemero et al. (2003) defines events as "changes in the layout of affordances" in the actor-environment system. Affordances are relations between the particular skills and abilities of the actor with respect to features and qualities of the environment (Chemero, 2003). Ideation drawings create changes in the affordances of the design situation, helping the designer explore concepts and perceive new opportunities to act upon. Drawings can expand the problem space because they allow designers to abstract ideas, emphasizing or disregarding aspects of the problem (Pereira and Tschimmel, 2012). In architecture, drawings and model making are both abstractions; the designer is unable to perceive affordances from the creative product itself because others build it after the design is finalized. Construction drawings are a blueprint from which to build the final product, but ideation drawings are physical forms of problem solving. Models serve a similar role in architecture, as abstracted, physical ideation (Yaneva, 2009, p. 57; Malinin, 2016). In jewelry making, however, the designer is able to also directly work with the materials of the final product.

Research on improvisational performance and design practices provides evidence that creativity does not begin with an idea in the head that is subsequently realized; it emerges through interactions with others and artifacts of the material environment. There is some evidence to suggest that other forms of creativity are similarly emergent and distributed, such as scientific (Watson, 1968; Gruber, 1981; Glăveanu et al., 2013; Malinin, 2016) and literary (Kipling, 1937; Glăveanu et al., 2013; Malinin, 2016) domains. Studies of real-world creativity also demonstrate how the phenomenon is transformative. Expertise changes perceptional abilities, instantiating events change affordances to be perceived, affordances provide opportunities for actions that shape creative products, which, in turn, change the creator. Creativity, thusly, can be characterized as a dynamical system encompassing brain, body and world — in line with the RECS perspective. However, the question of whether creativity requires mental representation remains.

In *The Reflective Practitioner* (which argued against Technical Rationality, rooted in CC)[4] Schön (1983) stated that designers "know more than they can say" (p. viii), that their knowing is embedded in their practice of creating (p. 60). Baber (2015, 2019) makes a similar argument, using examples from jewelry design to suggest how creativity need not rely on stored mental representations (Baber, 2015, pp. 33–34). He proposes creativity emerges through "opportunities within a space of constraints" (Baber, 2019, p. 229). By manipulating tools and materials, through "routine, improvised, or opportunistic action," people are changing the information they embody (p. 233). He illustrates how people (a) arrange their workspace to support creative activities, (b) arrange components of the design project, (c) arrange the body in anticipation of completing a task, (d) and respond to perceived changes in the materials or tools of a creative situation to suggest that creativity is a form of *technological reasoning* (p. 232). Similarly, Rietveld and Brouwers (2017) use their study of architectural creativity to argue that "the dichotomy between 'lower' and 'higher' cognition is largely artificial. . ." (p. 545). They advocate for a framework focused on skilled intentionality that integrates research on material affordances (the focus of most design creativity research) and social coordination (the focus of most improvisational creativity research). They suggest creativity can be characterized by skilled

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[4] See Chapter Two: From Technical Rationality to Reflection-in-Action.

activities unfolding in a complex situation, rich with affordances. Both proposals suggest creativity might be best understood as a self-organizing dynamical system. Baber focuses discussion around how the designer tends to navigate multiple affordances to "minimize risk, effort and other costs and maximize benefit and quality of the outcome" (Baber et al., 2019, p. 283) Whereas Rietveld and Brouwers use the concept of *optimal grip* to describe a type of skillful coping in the presence of multiple affordances, as an optimal actor-environment relationship. They explain how architects tend toward optimal grip in visual perception, optimal grip on the design project, and optimal grip on "how to design." Together these perspectives suggest how creativity is a form of distributed cognition involving bodily, material/technological, socio-cultural, and temporal dimensions, presenting a similar thesis, focused around the role of perception-in-action, to account for creativity in absence of stored mental representation.

Dynamic systems theory approaches to creativity, particularly music and design domains, have yielded new insights into the role of the socio-material environment in the development of creative expertise. Such insights are critical for better understanding how to teach skills associated with creativity. Schön's (1983) seminal work describing thinking-in-action, although not specifically informed by DST, remains influential for informing pedagogical practices in design, nursing, and teacher education (Burton, 2000; Webster, 2008; Sator and Bullock, 2017). More research is needed, informed by 4E cognition and DST, to identify specific pedagogical practices that lead to creativity. A recent article by Schiavio and Van der Schyff (2018) outlines a 4E framework to inform music pedagogy that bridges concepts of autopoiesis and DST to describe the reciprocal nature of social and material interactions involved in musical skills development. Theirs is an important first step that can help to inform future efforts in other domains, as well as across domains more generally.

DISCUSSION (EMBODIED CREATIVITY MATTERS)

Creative thinking is an essential skill for the future workforce (Barbot et al., 2015; Jules and Sundberg, 2018) and crucial for solving wicked[5] societal problems, such as overpopulation, poverty, and climate change. However, creative process research has largely stalled (Dietrich, 2007; Fryer, 2012; Glăveanu, 2014b; Barbot et al., 2015) and has not been particularly useful for informing educational psychology or pedagogical practices (Plucker et al., 2004; Glăveanu, 2014b; Sawyer, 2018). The field of creativity research is in crisis because, Glăveanu (2014a, p. 2) argues, "one of the most pervasive separations creativity researchers make is between creator (or his brain) and the social and material world." The body plays a key role in cognition (Gallagher, 2018), which has implications for embodied approaches to learning and development of professional expertise, including creative talent, and the design of environments where these occur. Thus there remains an untapped potential for embodied creativity to inform the design of learning spaces and instructional practices, better preparing the future workforce to solve critical societal and ecological *grand challenges*.

Analysis of the current state of embodied creativity research suggests some promising directions —but also that there is much work to be done to define and focus efforts in this nascent sub-field of creativity. Metaphorical creativity approaches mainly align with a *weak embodiment* perspective and grounded cognition. They do provide compelling evidence that the body shapes *creative mindset*, or disposition toward a creative situation. To date, this research stream is most relevant for informing learning environment and workplace strategies to improve *creative potential*. For example, building designs might take into account how thermal control could be strategically used to enhance creative thinking. Room configurations and building landscapes might be designed to encourage free walking. Furnishings could facilitate different postures, gestures, or walking movements (such as treadmill desks) to support divergent, convergent, or associative thinking processes. Such efforts, however, would need to include educating users about how to exploit these features of their workplace or instructional settings to improve creative productivity. Some of the embodied metaphors studied align with common habits that historically creative people incorporate into daily practice (such as walking or holding a warm cup), suggesting future research efforts have the potential to inform specific instructional practices, such as how to reduce creative fixation. Finally, metaphorical creativity research could integrate a strong embodiment (RECS) perspective to examine "mental" processes commonly associated with creativity, such as imagination, incubation, and conceptual combination. Slepian and Ambady (2014) demonstrated how creation of novel embodied metaphors provides evidence of embodied simulation. Approaches such as theirs could lend new insights into, for example, the little understood phenomenon of creative incubation leading to insight.

Recent dynamical systems approaches in creativity research, primarily in improvisational arts and design domains, more closely align with RECS. This stream of research also has the greatest potential to address the conceptual, methodological, and theoretical issues creating the present day "crisis" in the field. First, research in this area reveals that the common definition of creativity, as the ability to produce something novel and useful, does not adequately describe creativity-in-the-wild (i.e., real-world creativity). Creativity is situated practice; it involves embodied experiences and is embedded in socio-material environments. Dynamical systems approaches also describe how creativity is enacted through person-environment interactions and distributed among technological-material artifacts and other people. It could also address the emergent nature of creativity, constituted through reciprocal and transformative social and material interactions. Such approaches have strong potential to yield new insights relevant for informing pedagogical practices to teach creativity. In acknowledging 4E creativity, it follows that traditional methodologies, including the dominant focus on

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[5] Rittel and Webber (1973, 1984) define wicked problems as complex societal challenges that are difficult to solve because knowledge is incomplete or contradictory, the problems are connected to other problems (and solving them can create new problems), there many people and other factors involved, and there is an economic burden in solving them.

experimental approaches using AUT and RAT assessments, are simply not sufficient (and probably not even appropriate) to fully understand creative skill development. Finally, theoretical approaches — such as Baber's (2019) concept of creativity as *technological reasoning* or Rietveld and Brouwers's (2017) notion that it involves *skilled intentionality toward optimal grip* — begin to address the demand for a new theoretical framework that integrates the historically siloed 4Ps of creativity research.

What, then, are next steps for embodied creativity research? First and foremost, a new definition of creativity is needed to describe creativity as situated practice, emerging through person-environment interactions (material/technological as well as socio-cultural). Second, new conceptual and methodological tools must be adopted, including developmental and dynamical systems approaches, to better understand person-environment relationships (for example, how and when technological artifacts are instrumental) throughout the creative process — as well as how these relationships evolve with acquired domain expertise. Third, a common theoretical framework, informed by RECS, would provide a starting point to integrate research in the 4P's, including the often overlooked workplace or classroom physical environment (creative press) and the emerging neuroscience of creativity research stream (creative process). Dynamical systems approaches highlight the role of perception in creativity. Skilled perceptual abilities can be taught, as is a focus of pedagogical techniques in design programs. Yet, there is little understanding of how perceptual abilities lead to creative expertise. Architectural settings, such as learning spaces, shape sensorimotor experiences, which, in term, shape perceptions of affordances available to inhabitants. However, creative press research has prioritized socio-cultural over material-technological environments. Neuroscientific approaches propose a predictive processing (PP) model[6] of creative perception (Gabora, 2011; Dietrich and Haider, 2015, 2017). Although PP is typically considered in representational terms (Kirchhoff, 2017), and, at best, a weak form of embodied cognition (Gallagher, 2015b). Synergies between PP and studies of creativity as a self-organizing system of mind, body, and socio-physical environment (Walton et al., 2014, 2015; Baber, 2019; Baber et al., 2019) might present a starting point. Developing creativity in educational (or workplace) settings is a complex endeavor — and one that has not benefitted enough from creativity research (Barbot et al., 2015; Sawyer, 2018). For creativity to become a learning competency, essential for the future workforce, research approaches must consider its multidimensionality to effectively inform pedagogical practices — and acknowledge the role of the body, artifacts, and the larger socio-material environment in the development of creative expertise.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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[6] Predictive processing models suggest that the purpose of the brain is to make predictions of the world, and that these predictions inform and constrain perception (Clark, 2015; Dietrich and Haider, 2017).

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Effective Deep Brain Stimulation for Obsessive-Compulsive Disorder Requires Clinical Expertise

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Background: Deep brain stimulation (DBS) is an innovative treatment for severe obsessive-compulsive disorder (OCD). Electrodes implanted in specific brain areas allow clinicians to directly modulate neural activity. DBS affects symptomatology in a completely different way than established forms of treatment for OCD, such as psychotherapy or medication.

Objective: To understand the process of improvement with DBS in patients with severe OCD.

Methods: By means of open-ended interviews and participant observation we explore how expert clinicians involved in the post-operative process of DBS optimization evaluate DBS effects.

Results: Evaluating DBS effect is an interactive and context-sensitive process that gradually unfolds over time and requires integration of different sources of knowledge. Clinicians direct DBS optimization toward a critical point where they sense that patients are *being moved* with regard to behavior, emotion, and active engagement, opening up possibilities for additional cognitive behavioral therapy (CBT).

Discussion: Based on the theoretical framework of radical embodied cognitive science (RECS), we assume that clinical expertise manifests itself in the pattern of interaction between patient and clinician. To the expert clinician, this pattern reflects the patient's openness to possibilities for action ("affordances") offered by their environment. OCD patients' improvement with DBS can be understood as a change in openness to their environment. The threshold for patients to engage in activities is decreased and a broader range of daily life and therapeutic activities becomes attractive. Movement is improvement.

Keywords: obsessive-compulsive disorder, deep brain stimulation, evaluation, decision-making, clinical expertise, radical embodied cognitive science, affordances

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INTRODUCTION

Deep brain stimulation (DBS) is an innovative treatment in psychiatry. Electrodes implanted in specific brain areas allow clinicians to directly modulate neural activity. DBS is effective in reducing symptoms of patients with therapy-refractory obsessive-compulsive disorder (OCD) (Alonso et al., 2015). Since its introduction in 1999, 200-300 OCD patients have been treated worldwide. In contrast to established forms of treatment for OCD, such as psychotherapy or pharmacology, DBS affects symptomatology in a completely different way. DBS effects can occur very rapidly, sometimes in a matter of seconds (de Koning et al., 2016). Various OCD symptoms change on different time courses, with mood frequently improving almost instantaneously, obsessions over the course of weeks, and compulsions taking months to improve. It is unclear whether acute effects are predictive for long term improvement. Furthermore, DBS induces a broad range of changes in the phenomenology of patients, many of which are not captured by standardized clinical rating scales, such as the Yale-Brown Obsessive-Compulsive Scale (YBOCS) (de Haan et al., 2013, 2015, 2017). Moreover, patients themselves are initially often not aware of rather pronounced DBS-induced changes in their symptoms. This makes the effects of DBS difficult to interpret and to manage. The objective of this study is, therefore, to explore the process of improvement with DBS in patients with severe OCD.

MATERIALS AND METHODS

Setting

This study was conducted at the Psychiatry department of the Amsterdam University Medical Centre, location AMC. Since 2005 these clinicians have been treating over 80 therapy-refractory OCD patients with DBS in the ventral anterior limb of the internal capsule (vALIC). Their clinical expertise offers a unique perspective on the effects of DBS on patients. In this study, we try to understand the effects of DBS from the perspective of expert clinicians involved in the process of DBS optimization.

Deep brain stimulation optimization is a post-operative treatment phase in which the electrical stimulation is optimized with regard to symptom reduction and side effect suppression (Morishita et al., 2014). DBS optimization is an iterative process in which evaluation of DBS effects takes a central role. First, clinicians adjust stimulation parameters, like voltage, frequency, contact configuration, and pulse width. Second, they evaluate the effects of each such adjustment on OCD symptoms. Based on this evaluation they make further adjustments in stimulation parameters, and so on and so forth.

Interviews

All clinicians involved in DBS stimulation parameter optimization, which were four psychiatrists, two psychologists, and two specialized nurses, were interviewed for 2 h between July and November 2016. The interviews were open-ended, thereby minimally distorting with pre-defined categories the clinicians' descriptions of their own ideas and experiences. Two main questions were posed: "How do you characterize an optimal DBS effect?" and "What do you do to evaluate DBS effect?". Furthermore, we made use of a flexible topic list, which we adjusted when new topics emerged. When clinicians did not come up with a certain topic on our list, we addressed it ourselves at the end of the interview. Interviews were recorded and transcribed verbatim. Clinicians read their own and each other's transcripts and commented on it in a focus group.

Observations

The first author was embedded in the team and participated in the treatment process to the extent that he interacted with clinicians and patients, without performing any therapeutic actions *per se*. Clinicians were observed at various occasions: during their sessions with patients when stimulation parameters were adjusted, during weekly meetings of the multidisciplinary treatment team, training sessions for new DBS clinicians, brainstorm sessions on new strategies of optimizing stimulation parameters, and sessions of additional therapy, such as cognitive behavioral therapy (CBT). Observations were performed over an extended period of time (October 2016 – September 2017), which made it possible to repeatedly observe similar situations, and to track the over-all treatment process of several patients. This amounted to 130 h of observations, which were recorded in detailed field notes (Emerson et al., 2011).

Theoretical Framework

We understand clinical expertise in relation to skills. Skills can be studied with regard to the way in which experts are *situated* (Rietveld, 2008). Experts, on the one hand, are situated in their direct surroundings. When one focuses on particular real-world situations, it is possible to observe at which aspects of their surroundings clinicians are directed and how they interact with it. In the section "Results" we will call this focus on the particular situation *the zoomed-in perspective*.

On the other hand, we assume that experts are situated in a sociocultural practice. In a practice, skills are developed and sustained in relation to others. Given that they share skills, various members of a practice act in more or less regular and stable ways (Rietveld and Kiverstein, 2014). By observing multiple clinicians repeatedly and over an extended period of time, we are in the position to trace the regularities in behavioral patterns that are characteristic for the expert practice of DBS optimization (van Dijk and Rietveld, 2017). In the section "Results" we will call our focus on these regularities *the zoomed-out perspective*.

So, understanding expertise in relation to situatedness makes us not only pay attention to what clinicians say, but also to what they do, to their interaction with particular details of their social and material surroundings, and to regular ways of doing things that are shared by different clinicians (Greenhalgh and Swinglehurst, 2011).

Analysis

We believe that there is no predefined right or wrong answer to the question how the effect of DBS can best be understood. Instead, we assume, it is more productive to assess the (clinical) relevance of our interpretation of what this effect looks like. This was done by means of theoretical sampling and triangulation, which are important methodological tools to keep an open view and reduce the possibility of bias (Mol, 2002; Corbin and Strauss, 2008). *Theoretical sampling* implies going back and forth between data-acquisition and data-interpretation: hypotheses generated in earlier interviews and observations were tested in subsequent interviews and observations, which made it possible to prove and disprove preliminary interpretations, including those that might be based on preconceived notions of the authors. This resulted in a back-and-forth process in which theoretical insights were gradually developed and sharpened by practice. *Triangulation* implies the cross-checking of different data-sources: interpretations of what a clinician had said during an interview were compared to observations of how this clinician acted in practice. Moreover, we asked clinicians to give feedback both on the presentation of our results in a focus group with them and on preliminary versions of this paper.

RESULTS

We present our findings by means of a selection of fragments from observations and interviews. These fragments should prove their relevance by giving the reader an understanding of what DBS effects look like from the perspective of an expert clinician.

Zooming In: A Particular Clinical Situation

Every session, clinicians evaluate the effects of their latest adjustment in stimulation parameters and, consequently, decide whether additional adjustments are required. Below is a description of how such a session usually begins. The patient, Mrs P. returns to the outpatient clinic 2 weeks after her DBS has been switched on.

> Mrs P. is seated with her back toward us and the clinician calls her name. She turns around. Contrary to last time, we see a woman with colorful clothing. The clinician extends his hand, whereupon she returns a broad smile. The clinician introduces me [the first author]: "you already know each other, right?" Then, with a gesture, he invites her to walk in front of him to the consulting room. While walking, he asks: "You bought a puppy. How is she?" "How wonderful that you remember that!" Mrs P. replies. The clinician responds by making a small joke. The clinician walks quite fast, with the patient struggling, but succeeding, to keep up. While walking he asks her whether she wants coffee, tea, espresso, or cappuccino. After shaking hands with the junior residents who were waiting in the consulting room, the clinician is seated in front of Mrs P. and reclines. Mrs P. begins by mentioning that she is doing well, upon which the clinician replies: "I can see it."

We chose to highlight this particular situation because it shows how fast and intuitive the evaluation of DBS effects can be. The example indicates how a skilled clinician rapidly obtains an impression of how the patient is doing. Notably, this happens already before they have arrived at the consulting room. Once there, the clinician will ask the patient systematically how intense her obsessions are and to what extent she can resist performing compulsions. Yet, without having asked any such formal questions, the clinician can already *see* that Mrs P. is doing well, and that, consequently, no additional adjustments in DBS stimulation parameters are necessary.

The clinician's evaluation that it is going better with the patient is not solely the result of the patient saying so. In various ways he has gathered knowledge on how Mrs P. is doing. That knowledge was not just there, it has been actively obtained. By performing various kinds of actions, we noticed, clinicians elicit certain responses in the patient, which inform them on the effects of DBS. **Table 1** gives a (non-exhaustive) list of things clinicians do to assess how the patient is doing.

Which of these listed action possibilities is relevant at a given moment is determined, amongst other things, by the social and material structure of the outpatient clinic. The hallway with the coffee machine, for instance, affords making light conversation, whereas the possibility of asking serious personal questions about the patient's OCD becomes appropriate only in the privacy of the consulting room. Furthermore, the custom of introducing people to each other in combination with the researcher's presence at their interaction in the waiting room makes it relevant to the clinician to direct the patient's attention to the researcher. When the concrete situation in which clinicians' decision making takes place is taken into account this brings into view that, to some degree, their actions are structured by their social and material surroundings.

Moreover, we observed that clinicians act in response to a dynamically changing situation. As the situation is changed by the clinician's and patient's actions, new possibilities for action arise. The clinician's action of asking the patient about her dog, for example, leads to a response of the patient ("how wonderful that you remember that!"). Her response, in turn, invites the clinician to respond by making a joke, and so on, and so forth.

There is no single clear-cut decision-making moment. Clinical judgment is not confined to the moment in which stimulation parameters are adjusted or when the YBOCS is scored. It already

TABLE 1 | Diagnostic actions.

Extending a hand
Calling a name
Smiling
Presenting the patient with a choice (for coffee, for various treatment options)
Waiting for the patient to take the initiative
Chit-chatting
Making a joke
Asking questions (about the patient's dog, about the severity OCD symptoms)
Asking for a clarifying example
Consulting the opinion of family-members
Being alert for a casual remark (for instance about forgetting compulsions)
Rating clinical scales, such as Yale-Brown Obsessive-Compulsive Scale (YBOCS)
Adjusting DBS stimulation parameters
Encouraging the patient to do a small exposure exercise

takes place in the long chain of actions preceding the moment in which the clinician says "I can see it." As the clinician responds to the dynamically changing situation, by asking questions, rating scales, and making jokes, his judgment is gradually sharpened.

Taken together, by zooming in on particular clinical situations we found that evaluating DBS effects is an (a) interactive and (b) context-sensitive process that (c) gradually unfolds over time, and (d) requires integration of different sources of knowledge.

Zooming Out: Across Multiple Sessions

In this section we take a perspective that stretches across multiple sessions. Every session clinicians make one single adjustment in stimulation parameters. This is repeated until they consider that an "optimal" effect has been established. But what is this "optimal" effect?

Optimal is best understood in contrast to sub-optimal or non-optimal. Below is an interview quote from a clinician who describes how he had been treating a patient with CBT. Before patients are qualified to get DBS the completion of at least one course of CBT is required. A central element in CBT is *exposure with response prevention*, which implies that a patient needs to confront an anxiety-provoking situation without performing compulsions. When sustained and repeated, the patient will learn that the consequences she fears do not occur and that compulsions, therefore, are not necessary.

Below, the clinician describes how he was unable to engage the patient to do the exposure exercises. Her anxiety was simply too strong. He had been "pulling and pushing," "trying every other technique," but his attempts failed. He contrasts this with what happened when the patient got DBS and this started working:

> "What we asked her to do in therapy, before she had DBS, for at least 100.000 times, she now sees as an achievable option. [. . .] Suddenly she could reflect, could finally say 'I just did it, I did not perform the compulsions'. There was, as it were, more space in her head to look at her emotional life differently. That was really remarkable. I have seen this woman in therapy before and back then she could not *be moved*. [our italics]."

The clinician who first "pushed and pulled" in vain can now feel that the patient is *being moved*. *Being moved* is a characterization that captures the contrast between a responsive and an unresponsive OCD patient. This characterization indicates a change in the patient's pattern of responses. Expert clinicians share a sensitivity to this kind of change. They keep optimizing DBS stimulation parameters until they sense that this change in responsiveness has occurred.

The interview quote captures our general finding of how the phenomenon of *being moved* reflects change in three interrelated domains: (1) behavior, (2) emotion, and (3) active engagement. First, there is movement in a literal, behavioral sense. Clinicians observe an "expanding perimeter" of patients' life worlds as they spend less time and energy on compulsions and stop avoiding places. Patients open up to a broad range of daily life activities, instead of being restricted to a narrow range of compulsive actions.

Second, patients are also moved in an emotional sense. This is illustrated in the case of a patient who, upon looking around after her DBS is switched on, sees her husband in tears and promptly starts to cry herself. Clinicians sense that patients are more easily motivated: the "threshold for engaging in various kinds of activities has been lowered" and "blockages and inhibitions decrease." Clinicians are emotionally involved in this process themselves. The frustration and dissatisfaction they feel when they push and pull in vain over and over again makes way for enthusiasm and hope as they sense that the patient is being moved.

Third, patients are being moved in the sense that they can be *more actively engaged* in their process of recovery. Clinicians notice that their relationship with the patient becomes more interactive and reciprocal. They are no longer "pulling and pushing" alone and in vain. We observed, for instance, how an OCD-patient who was admitted because she feared harming herself and others suggested she might go home for short periods of time to do little tasks, as watering plants or checking mail, to expose herself gradually to the fear of being at home on her own. More generally, DBS clinicians regard this change in attitude a "window of opportunity", as the patient's active participation opens up possibilities for additional psychotherapeutic interventions, such as CBT, which require patients to be actively engaged in their process of recovery.

DISCUSSION

Summary of the Findings

We studied how clinicians evaluate DBS effects to understand the process of improvement with DBS in severe OCD patients. We described this process from two perspectives. The first zoomed in on what happens within one treatment session. The second perspective zoomed out across multiple sessions to characterize the change that the different clinicians aim to establish in patients over time. The zoomed in perspective reveals that evaluation of DBS is (a) an interactive and (b) context-sensitive process which (c) gradually unfolds over time and (d) requires integration of various sources of knowledge. The zoomed out perspective reveals that clinicians adjust DBS settings gradually up to the point where the patient is *being moved* with regard to behavior, emotion, and active engagement.

Implications

Although this study is the first to specifically focus on the perspective of expert clinicians, it is not the first to explore the effects of DBS in OCD. Our research group did phenomenological interviews with 18 OCD patients on the way in which DBS impacts their "lived experience" and field of action possibilities (de Haan et al., 2015, 2017). Other authors, who also use a target in the internal capsule, have interviewed 9 OCD and 6 MDD patients on their experiences of how DBS impacts their actions, decision-making and relationships (Klein et al., 2016). The findings of these studies converge with our finding that, for most patients, the threshold to engage in activities is decreased and a broader range of action possibilities becomes attractive instead of just the narrow range of compulsive routines.

Together with findings from the two interview studies in patients, our study may shed new light on the ethical debate about DBS. It is puzzling so far to know whether and to what extent DBS threatens or supports agency, autonomy, personal identity, and the self. In this debate several authors conceptualize agency as a relational and gradual phenomenon (Baylis, 2013; de Haan et al., 2015, 2017; Goering et al., 2017; Gallagher, 2018). In a relational understanding of agency the DBS device is seen as just one of many aspects that, together, influence the patient's ability to reach goals, like family members, clinicians, and smartphones do. In a view where many aspects co-determine a person's agency it makes sense to see the difference in agency of typical people and OCD-patients as a matter of degree. This is also what we found: when DBS starts working the openness to a range of action possibilities gradually increases.

The effects of DBS involve mechanisms of action on different levels of complexity (Jakobs et al., 2019). Our finding of how patients with DBS open up to a broader range of action possibilities resembles the construct of *cognitive flexibility*, which is described as the ability to shift the focus of attention and to acquire new responses in the face of changing environmental demands. Improvements in cognitive flexibility with active DBS have been associated with the activity of distinct brain networks in 5 OCD patients (Tyagi et al., 2019) and with particular patterns in oscillatory activity of frontal neural populations in 2 OCD and 12 MDD patients (Widge et al., 2019).

Given the fact that not only OCD but also MDD patients are included, the above discussed interview and mechanistic studies indicate that the effect we found might be more broadly applicable than to our limited case of OCD alone. Increasingly *being moved* with regard to behavior, emotion, and active engagement may be a general effect of DBS, at least for this capsular site.

Relating Perspectives Using Radical Embodied Cognitive Science

We studied the improvement with DBS in OCD patients by interviewing and observing clinicians. In order to show how the perspectives of clinician and patient are integrated, we will now analyze our findings in terms of the theoretical framework of radical embodied cognitive science (RECS) (Thompson, 2007; Chemero, 2009; Noë, 2012; Bruineberg and Rietveld, 2014; McGann, 2014; Gallagher, 2017; Rietveld et al., 2018). Like the relational and gradual view on agency discussed above, RECS takes into account how a person is *situated* within a broader context. More in particular, RECS focuses on the dynamics between an individual and its environment, regarding an individual's actions as ways of *responding* to the possibilities for action (affordances) the environment offers.[1]

In radical embodied cognitive science terms, patients and clinicians can be seen as parts of each other's environment. By changing the shared situation in particular ways, as was described in the first part of the section "Results," clinicians get feedback on the patient's responsiveness to action possibilities. Somewhat like a wrist is palpated to find out whether it is broken, DBS clinicians systematically probe (Harris, 2015) the OCD patient's responses. For instance by extending a hand or by asking a question, expert clinicians create possibilities for action for the patient (to shake the hand, to answer the question), putting themselves in a position to assess which action possibilities a patient does and does not respond to.

This integrated understanding of what a patient does and does not respond to is what in RECS terms can be called the patient's *selective openness* to possibilities for action (Bruineberg and Rietveld, 2014; Rietveld et al., 2018). Selective openness implies that at any given moment some possibilities for action are more attractive to a person than others. It is precisely because clinicians continuously attune to the selective openness of the patient (zoomed in) that they are able to sense when the patient is being moved, that is, when the patient's selective openness changes (zoomed out).

So, expert clinicians' sensitivity to when patients are being moved by DBS rests on their ability to attune to the patients' responses. This ability to attune to OCD patients, we assume, is the result of many interactions with OCD patients in the past. This is knowledge in a form that cannot be straightforwardly translated into words or numbers. It is embodied knowledge. It is knowing how to respond appropriately to a particular patient in a particular situation. This knowledge, as we displayed in this study, can be studied when one zooms in on these particular situations and observes how clinicians interact with patients.

DBS as a Holistic Treatment

When OCD patients have reached the point where they are *being moved* they are not there yet. This point marks the beginning of a transition in which patients are more and more engaged in their process of improvement. As the patient is being moved, new action possibilities emerge, both for the patient and the clinician. One of these possibilities is CBT, in which remaining symptoms are reduced and healthy behavioral repertoires are expanded. Engaging in CBT is crucial for recovery. If one stays at home, without engaging in new action possibilities, clinicians observed, old habits will eventually return. The movement which was initiated by DBS needs to be kept going.

The importance of actively engaging in new action possibilities, of seeing *being moved* as the beginning of a transition, shows how DBS and CBT are mutually reinforcing treatments. DBS creates the conditions for CBT and CBT, in turn, increases DBS efficacy (Mantione et al., 2014) and prevents relapse. The relation between DBS and CBT also shows how, from the perspective of expert clinicians, diagnosis, and treatment are interrelated. Already during the optimization of DBS stimulation parameters, clinicians start with small CBT exercises. When these exercises are successful this is *therapeutic* in the sense that a patient learns that what she fears does not occur. At the same time the CBT exercise is also *diagnostic*: it informs the clinician whether the stimulation parameters of the DBS are effective or not.

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[1] The technical term for possibilities for action is *affordances*, which was first introduced by Gibson (1979). In earlier work we have defined affordances as relations between aspects of the sociomaterial environment in flux and abilities available in an ecological niche or practice (Rietveld and Kiverstein, 2014; Rietveld et al., 2018).

The way in which expert clinicians integrate DBS and CBT and diagnosis and treatment stresses the importance of seeing DBS treatment as holistic. Holism, from a RECS-perspective, means that a patient (or brain) is not regarded in isolation, but as part of a larger brain-person-environment system. This holism is reflected in the skills of expert clinicians, who are open to a range of action possibilities offered by the different aspects of this brain-person-environment system. This includes the possibility of adjusting DBS stimulation parameters (thereby affecting the patient's brain) as well as the possibility of, say, taking the patient outdoors for an exposure exercise (thereby changing the patient's environment). Both interventions have the potential to affect how the patient relates to his or her environment.

Limitations

A limitation of this study is that its findings cannot be expressed in quantitative terms. Our qualitative work can be seen as complementary to studies that use quantitative means of evaluating OCD improvement, such as the YBOCS (Denys et al., 2010). Moreover, explorative studies like ours can open up new directions for quantitative enquiry. Based on our findings one might, for example, operationalize the clinicians' strategy of evaluating DBS effects in terms of changes in the way patients relate to their environment. Simple tools like GPS-trackers could, for instance, quantify the expanding perimeter of a DBS-patient's activities in the living environment as his or her openness to the world increases.

A further limitation is that the authors, as a result of their professional and academic backgrounds, have expectations that might have biased data-interpretation. Having published on RECS before, the authors have a tendency to interpret their current findings in light of this past work. Additionally, the first and last author are clinicians themselves, which could have limited their ability to ask "naïve" question that might probe clinicians to explain basic aspects of their practice. We have tried to minimize the possibility of bias by means of theoretical sampling and triangulation. Moreover, we believe that our particular backgrounds and related attitudes are important as they shape our sensitivity to aspects of the practice of DBS optimization that remain often out of view (Mol, 2002, 2008).

This study foregrounded the perspective of clinicians. This, however, does not mean that we see patients as mere passive subjects. What's more, their active participation in the treatment is crucial to its success. Our research shows that clinicians are directed at creating conditions for the patient to become actively involved in his or her process of improvement. Furthermore, in earlier work our research group described DBS-induced changes in the phenomenology of OCD patients who are comparable to the patients figuring in the present study (de Haan et al., 2013, 2015, 2017). In contrast to this former study, we focused primarily on the clinicians and the activities they perform to assess and establish these DBS-induced changes. Via a different route, our study on clinicians nevertheless arrived at the same conclusion: in both studies the effect of DBS has been characterized as a restructuring of patients' openness to the world.

The emphasis we put on clinicians' responsiveness might make it seem like everything they do always goes smoothly, almost effortlessly. However, note that we also described how clinicians were initially "pulling and pushing" a severely ill patient without success. Only for reasons of clarity, we chose not to include more descriptions of episodes in which attempts to improve a situation failed. For the same reason, we did not include situations in which clinicians were in doubt or were engaged in multidisciplinary discussions[2], as happened with patients that did not respond to DBS, that suffered from intolerable side effects or whose comorbid disorders interfered with the treatment.

Finally, it is not clear to what extent our findings apply to other DBS centers, where things are organized differently (e.g., not all centers add CBT to DBS, not all centers implant the electrode in the vALIC), or to other OCD treatments, and DBS in other illnesses, such as Major Depressive Disorder and Parkinson's Disease. Nevertheless, we believe that the importance of attuning to a patient is something many clinicians will recognize. This study has tried to make a case for why clinical expertise is so important to effective treatment.

CONCLUSION

Obsessive-compulsive disorder patients' improvement with DBS can be understood as a change in selective openness and responsiveness to their environment. The threshold for patients to engage in activities is decreased and a broader range of action possibilities becomes attractive to the patient instead of just the narrow range of compulsive routines. Clinical expertise enables clinicians to attune to the patient's responses and, thereby, to sense this DBS-induced change. From that moment on, patients can be actively engaged to further expand their openness to the world by means of additional psychotherapeutic interventions, such as CBT.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethics approval was not required as per applicable institutional and national guidelines and regulations. Based on the Research Involving Human Subjects Act (Wet Medisch-Wetenschappelijk Onderzoek met Mensen), the Medical Ethics Review Committee of the Academic Medical Centre (AMC), Meibergdreef 9 in Amsterdam, Netherlands, declared that no official approval was required as our study did not subject persons to interventions

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[2] Nevertheless, based on our earlier work we think that reflection fits in with the RECS-approach we described: concrete socio-material situations include things other people say and offer possibilities for reflection as well (Rietveld and Kiverstein, 2014; Rietveld et al., 2018). We aim to discuss this in relation to our observations in future work.

or behavioral regulations. The clinicians, who were the primary participants of this study, provided verbal informed consent to being interviewed and observed and were offered the opportunity to read and comment on this manuscript. Sessions where patients were present were only attended when the patient provided verbal informed consent to the researcher's attendance and anonymized field note taking. Written informed consent was obtained from Mrs P. (not her real initials) for the publication of the case description in this article, including all identifiable information.

AUTHOR CONTRIBUTIONS

MW and ER performed the interviews. MW did participant observation. MW analyzed the data. MW wrote the first draft of the manuscript. All authors contributed to the conception, design of the study, manuscript revision, and read and approved the submitted version.

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Towards an Embodied Signature of Improvisation Skills

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Improvisation is not limited to the performing arts, but is extended to everyday life situations such as conversations and decision-making. Due to their ubiquitous nature, improvisation skills have received increasing attention from researchers over the last decade. A core challenge is to grasp the complex creative processes involved in improvisation performance. To date, many studies have attempted to provide insight on brain activity and perceptual experiences when perceiving a performance, especially in musical or artistic form. However, watching/listening a performance is quite different than acting in a performance or performing daily-life activities. In this Perspective, we discuss how researchers have often missed key points concerning the study of improvisation skills, especially by ignoring the central role of bodily experiences in their formation. Furthermore, we consider how the study of (neglected) motor component of improvisation performance can provide valuable insights into the underlying nature of creative processes involved in improvisation skills and their acquisition. Finally, we propose a roadmap for studying improvisation from the acquisition of kinematic data in an ecological context to analysis, including the consideration of the coalition of (individual, environmental and task) constraints in the emergence of improvised behaviors.

Keywords: improvisation, creativity, expertise, motor signature, embodied cognition

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INTRODUCTION

In psychology, improvisation is typically conceived as a creative process without a script or anticipated preparation (Gueugnon et al., 2016a,b). The idea that improvisers spontaneously create a novel product *ex nihilo* rather than from a pre-existing material or substrate has a powerful intuitive appeal. Yet, this idea is not well supported by empirical evidence (Brown, 2000). Instead, improvised products that are central in many fields, including performing arts (e.g., music, theater or dance) and everyday life (e.g., improvising a dinner, a speech or actions in sport settings), are conceived to be shaped by the lifetime history of individuals, especially via their past (bodily) experiences and training (Chelariu et al., 2002). According to this perspective, each element is pre-existing, but the way improvisers can combine them is a unique creation of the present moment. Improvisers must therefore master a whole package of elements (i.e., constituting their repertoire) from which they gradually learn to build their own improvised composition (Azzara and Grunow, 2010). In this respect, improvisation expertise requires a large amount of practice and experience, leading to a myriad of perceptual, cognitive and motor changes over time (e.g., Ericsson et al., 1993; Pinho et al., 2014). Although expertise has long been at the heart of research in psychology, sports sciences and a wide range of other fields, studies dealing with improvisation expertise are paradoxically limited, and the underlying mechanisms of learning across the various stages of improvisation skills construction are largely unclear. A potential reason that limits our knowledge of improvisation skills could be the difficulty to capture the "higher-order cognitive processes" underlying improvisation performance in standardized laboratory tasks. To date, many studies have attempted to provide insight on brain activity and perceptual experiences when perceiving a performance, especially in musical or artistic form. Thinking from a broader perspective, we consider in this article that previous experimental investigative contexts are too limited such that the results may not extend to more complex realistic situations. In addition, we show that some key ideas from different disciplines have been overlooked in improvisation skills literature, such as the consideration of motor coordination in collective improvisation. Moreover, we believe that creativity can be more rigorously quantified by studying body movements in order to measure how people recycle motion (improvise) over time and determine whether the movement combination was creative (i.e., statistically rare) or not.

Improvisation and Creativity in the Arts

Improvisation is traditionally viewed as the essence of performing arts, when artists are devoted to an act of creation "on the spot" within a well-defined framework. It is therefore not surprising that the greatest scientific literature on improvisation can be found among the arts, namely music and dance (Pressing, 1984). In particular, much of our knowledge about improvisation comes from neuroimaging studies that shed light onto which brain regions are involved during dance/music perception (Calvo-Merino et al., 2004; Engel and Keller, 2011) or improvised music production (Bengtsson et al., 2007; Berkowitz and Ansari, 2008; Limb and Braun, 2008; Pinho et al., 2014). It is now well documented that improvisation is most commonly associated with activation of the premotor and prefrontal cortex areas (Pinho et al., 2014; Beaty, 2015), two cortical areas known to play a significant role in planning/initiation of voluntary motor movements (e.g., Lu et al., 2012) and creativity (e.g., Dietrich, 2004), respectively. Creativity, i.e., the capacity to generate both novel and meaningful events, constitutes thus a key element of improvised products. Although it is hard to differentiate creativity from improvisation since they are closely nested, what characterizes improvisation performance relies above all on its spontaneous character, its aesthetic values of perfection/imperfection and does not imply necessarily a radical novelty. In addition, improvisation has an intrinsic motor component that is not necessarily found in all domains of creativity (e.g., generating creative ideas) except for the specific case of motor creativity (Orth et al., 2017). In this context, we focus in this article on the motor aspect of improvisation performance, especially because what happens "outside the head" during performance remains largely under-explored in the literature. This is paradoxical when one considers that "*the primary instrument through which improvisation takes place is the human body and its interactions with other bodies*" (Carter, 2000, p. 182).

Improvisation in Real-Life and Skill Transfer

Little is known about improvisation outside the arts; however, improvisation skills occupy a central place in a broad landscape, from arts to sports to everyday activities. In sports such as football, basketball and tennis, the scenario of the match is unpredictable and players must constantly adapt their plans/actions to the current situation while respecting the framework defined by the rules of the game. Similarly, improvisational skills are crucial in situations where verbal and/or non-verbal communication can be challenging, such as communicating in a foreign language. It then appears necessary to extend the study of improvisation skills and their acquisition to a variety of tasks. The study of improvisational skills in different situations would help to uncover whether and to what extent skills are transferrable across tasks, domains, and/or disciplines. For example, are dancers' improvisational skills specific to the dance of which they are experts, or can they also be transferred to music or daily social situations?

Challenges of Measuring Improvisation

The quantification of improvisation can be challenging, from a neuroscience approach (e.g., using fMRI or EEG), because the use of novel tasks involving substantial body movements often generate measurement artifacts (Pressing, 1984). Therefore, there is motivation for alternative ways to quantify motor improvisation. The proposed approach therein overcomes this challenge by directly analyzing the flow of information conveyed by human movements in order to gain insights into the creative processes underpinning improvisation performance. This would be a viable strategy, as we strongly believe that improvisation skills are embodied in our action-perception synergies, such that our lifetime bodily experiences influence our improvisation skills, and in turn, our improvisation skills influence our body movements.

A NEW APPROACH TO IMPROVISATION GROUNDED ON MOTOR COMPONENT

Watching outstanding individuals' performance is simply captivating and attests to the fact that there is something special in the way they move. Moving bodies both receive and transmit a wealth of information about a person, including intentions, emotions, personality or identity that we can effortlessly perceive (e.g., Troje, 2002). There are good reasons to believe that improvisational skills, similarly to emotions or intentions, color movements. For example, it has been empirically demonstrated that movement qualities of expert improvisers differ from those of novices (Noy et al., 2011; Issartel et al., 2017). Using the *mirror game* (Noy et al., 2011), a simple yet effective paradigm

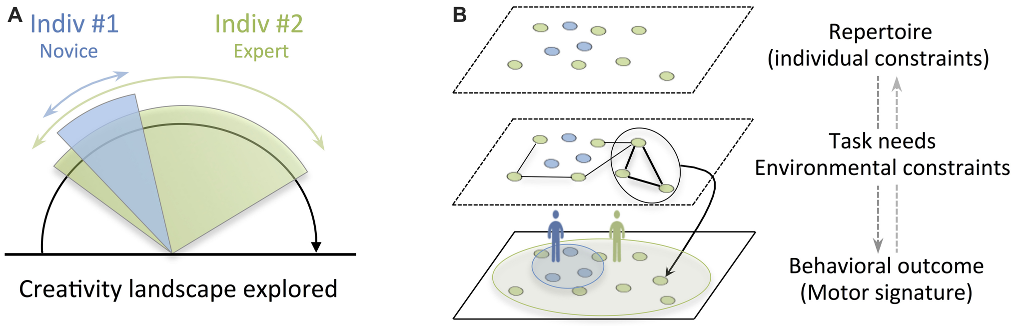

FIGURE 1 | (A) Schematic depiction of the motor creativity of two individuals with different levels of expertise in improvisation. The landscape of creativity explored by the expert (indiv#2) is supposed to be broader than that of the novice (indiv#1). **(B)** Illustration of the three layers leading to the emergence of improvised behaviors. The first layer corresponds to the individual repertoire formed largely by past body activity experiences. The second layer shows how behavioral solutions emerge through the exploration of the individual repertoire under external constraints (task and environment). The third layer corresponds to behavioral outcome - the observable part of the improvisation process at the behavioral level - which can be easily captured by means of movement analysis and made readable using dimension reduction techniques (e.g., multidimensional scaling to display the individual motor signatures). In this way, each individual's trial was plotted as a point on a map, so that similar trials are placed near each other and dissimilar trials are placed far from each other. The area of ellipses that encompasses all dots (experimental trials) of each individual provides a measure of within-person motor (intra-individual) variability (i.e., creativity landscape explored).

for studying two people improvising hand movements with different social roles (leader/follower/no designated leader), Noy et al. (2011) found that experts create more complex (i.e., creative) and synchronized motion than novices when there is no designated leader. In another behavioral study, Issartel et al. (2017) compared motion characteristics in the *mirror game* of three groups with distinct levels of expertise in improvisation dance (novice, intermediate, expert). Results revealed that each group had a very specific movement organization and that motor creativity increased with expertise. Thereafter, a series of studies attempted to provide insights into how these improvisation skills evolve over time from practice. For instance, Gueugnon et al. (2016b) showed that movement richness of novice pairs in the *mirror game* increased across time, but solely for dyads performing unintended synchronized movements. Taken together, these results suggest (i) the existence of a motor signature of improvisation expertise and (ii) improvisation skills can be enhanced through practice—as the old adage goes, "practice makes perfect." Thus, similar to athletes who rigorously follow an intensive training to perfect their technical, tactical and physical skills for performance purposes, improvisers must spend a large number of hours of practice devoted to skill-building. It is important to note however, that, except the work of Issartel et al. (2017), who conjointly studied both solo-improvisation and joint-improvisation to establish the influence of the social interaction, other studies related to the *mirror game* have addressed mainly joint coordination. Solo and joint improvisation differ in that joint improvisation incorporates (in addition to solo skills) dyadic coordination. This difference may have major consequences on improvised behaviors. For instance, Issartel et al. (2017) reported that movement richness in joint improvisation, where participants were explicitly asked to be coordinated, was significantly reduced compared to the solo condition irrespective of the level of expertise (novice, intermediate, expert). This finding suggests that both the (social) environment and the goal of the task (collaborative task) interact and play a crucial role in shaping improvisation behaviors.

THE ROLE OF CONSTRAINTS IN THE EMERGENCE OF IMPROVISED BEHAVIORS

There is now growing evidence that improvisers dynamically act and react according to a set of changing constraints (e.g., Newell, 1986), including individual constraints (e.g., level of expertise), task constraints (e.g., rules: improvising on a given theme) and environmental constraints (e.g., the presence of an audience). With this in mind, one can thus consider improvisation activity as an on-going dynamic process involving a search for adaptive and creative (motor) solutions to a variety of constraints. We argue that creative solutions that best fit the situation emerge through exploration, under the interacting constraints imposed onto the improviser (Orth et al., 2017), and that motor variability is a key component for improvisation expression. **Figure 1** illustrates our claim.

Each individual is assumed to have a more or less broad (behavioral) repertoire reflecting the ontogenesis/history of the individual, including past experiences and level of expertise (see the first layer of **Figure 1B**). This behavioral repertoire is enriched over time and (sensorimotor) learning, and serves as support for improvisation on which it feeds. Thus, during improvisation performance, the improviser can exploit existing elements from his/her own repertoire or explore new combinations of these elements according to the requirements of the task and the environment. This is manifested at the behavioral level either as a routine pattern of motions or as new ways of moving (Torrents et al., 2010). Relevant to understanding where the inspiration underlying improvisation comes from, it is necessary to examine the nature of constraints, namely the interaction between the individual, his/her surrounding environment and the task demands (see the second layer of **Figure 1B**). Inspiration is fleeting. A theme, a story, an emotion, an object, or the interaction with a partner can trigger it. For instance, in football, dynamic interactions between players (teammate and opponent) can lead to creative solutions (e.g., offensive or defensive strategies) that cannot be explained solely by the actions of each individual (i.e., the whole is greater than the sum of individual actions; Sawyer and DeZutter, 2009). Other factors may more or less account for the emergence of certain improvised products. This is at least the case for memory, which is known to encode, store and retrieve information from past events (Baddeley, 1997), and influences future actions (Gärling et al., 1997). Specifically, research has demonstrated the crucial role of working memory in imagination and creativity capacities, enabling the construction of original materials using a fraction of all the information "stored" in participants' memory, those recalled and manipulated at a specific instant of time (Ockelford, 2012). Time plays a major role since both memory and improvisation operate at different time scales, from a fraction of seconds (working memory/improvised motor act) up to a lifetime (long-term memory/expertise acquisition). Despite the fact that the working memory and the long-term memory operate at different time scales, some authors consider working memory as part of long-term memory and have introduced the notion of "long-term working memory" (Ericsson and Kintsch, 1995; Ericsson and Delaney, 1999). The idea behind this is that lifelong knowledge/skills/information acquired through learning/experiences and stored in long-term memory are kept directly accessible by means of retrieval cues in working memory (Ericsson and Kintsch, 1995). Given the spontaneous character of improvisation performance, we believe that the temporal constraint significantly shapes improvised behaviors. The generation of behavior on a fast time scale would be mainly determined by previous training and learned automatisms, and is therefore likely to be "less" original than the generation of behavior on a slower time scale. Exploration phases of new improvised behaviors indeed require much longer time than the exploitation of existing improvised behaviors. We also believe that social interactions, as part of environmental constraints, significantly shape our repertoire and constitute a real catalyst for the discovery of novel behaviors. This is based on a large body of evidence suggesting that when we move with other people, the overlap between action observation and action execution is responsible for a process of motor interference (or contagion) that arises during both transitive (goal-oriented actions; Hardwick and Edwards, 2011) and intransitive (non-goal-directed actions; Kilner et al., 2003) actions. In joint improvisation tasks, since individuality challenges interpersonal motor coordination, individuals must partially or totally lose their individual preferences to behave similarly to their partner at the time of interaction, therefore expressing a certain type of behavioral plasticity. Słowiński et al. (2016) and Hart et al. (2014) reported substantial changes in individuals' motor behaviors (signatures) upon social contacts (environmental change). Such behavioral changes induced by social interactions may persist even after the encounter is over, the so-called social memory effect (Oullier et al., 2008; Nordham et al., 2018). However, differences can be expected depending on the purpose of the task (spontaneous or intentional motor coordination). In the case of spontaneous settings, individuals are "freer," so they can create more complex and unusual motion patterns without worrying about (the coordination with) their partner. However, they can lose the potent beneficial effect of entrainment on social memory, as the quality of the information exchanged during spontaneous interaction is degraded compared to that of intentional coordination. On the other hand, intentional coordination often suffers from a lower creativity level (Issartel et al., 2017) in order to produce simple patterns of movement that are easy to predict (Hart et al., 2014), but social memory may nevertheless benefit from the effect of entrainment. Future studies can potentially address these issues by investigating the effect of constraints on improvisation capacities.

MOVING FORWARD

In this Perspective article, we emphasized that improvisation skills are not purely cognitive products but are shaped and expressed through body motion. Extracting and analyzing the continuous stream of information offered by movements during a performance opens new promising avenues for a better understanding of the creative and learning processes involved in improvisation.

Our proposal for studying improvisation can be summarized as follows:

(i) *Capturing the essence of improvisation in motor performance in the most naturalistic and reliable way as possible*. The *mirror game* (*MG*) seems to be a good model (see Noy et al., 2011; Feniger-Schaal and Lotan, 2017 for full body 3D mirror game) because it provides a good balance between naturalistic (social) interaction and controlled interaction inspired by one of the most common drama exercises. In addition, *MG* entails all the ingredients to provide access to the motor expression of creative processes. That is, it enables exploratory behavior in which participants play together and search for various interesting patterns of movement by varying both amplitude and frequency of motions during the trial. Movement patterns during *MG* contrast thus with the simple rhythmic movements (mono-frequency and fixed amplitude) traditionally obtained in coordination studies with very restrictive motor tasks such as pendulum oscillation (e.g., Coey et al., 2011), finger tapping (e.g., Nowicki et al., 2013) and rocking-chair (e.g., Richardson et al., 2007). *MG* has however some limitations for the study of improvisational skills. First, *MG* might primarily be an exercise in coordination rather than improvisation, with interpersonal coordination playing a major role in joint improvisation. We therefore suggest that *MG* can be employed as a model for studying the effect of coordination on joint improvisation performance (dyad) or collective performance (group more than two players – Alderisio et al., 2017). As a precaution, solo performance should be evaluated first, as well as just after the interaction, to assess the effect of interpersonal coordination on individual behaviors and the persistence of these changes over time. A second limitation of *MG* is that the original experimental (one-dimensional) set-up is oversimplified, and therefore may not account for non-trivial daily activities such as driving a car or talking to another person, which are all more or less improvised from both motor and cognitive points of view. Moreover, it does not allow to investigate properly solo improvisation skills or the aesthetic quality of the performance. Consequently, further investigations in more ecological solo and collective improvisation tasks seem particularly relevant. To this end, researchers can rely on recent technological advances in 3D motion capture (e.g., marker-less tracking) and in (big) data analysis with artificial intelligence algorithms to better understand both individual and collective improvisation across various contexts (artistic, sports, as well as daily).

(ii) *Using relevant metrics to analyze kinematic data to infer the underlying creative processes involved in the improvisation performance and to identify key features of expertise*. We suggest that the extraction of behavioral signatures (e.g., Słowiński et al., 2016) can help us to discriminate creativity in participants and relate it to their levels of improvisation expertise. For example, Słowiński et al. (2016) proposed an index able to capture the subtle differences in the way each person moves in *MG*. Both intra- (between trials) and inter-personal (between players) motor variability was used as input to demonstrate that the individual motor signature of a person is time-invariant and that it significantly differs from those of other individuals. Interestingly, the authors noticed that some participants had a quite specific way of moving that was preserved over time (i.e., across trials) while others tended to change their movement between trials. In light of the instructions given to the participants—"*Play the game on your own, create interesting motions and enjoy playing*"—this intra-individual motor variability seems to somehow reflect participants' creativity. We strongly believe that motor variability might be a reliable marker of creativity. The underlying assumption is that creative motor solutions arise – in some manner – from the continuous stream of variations in motor acts. The larger the variability, the more likely it corresponds to a (statically rare) creative motor solution (Orth et al., 2017). A deeper analysis of improvisation skills can be done by measuring the level of performance, particularly in the achievement of the final goal of the task. In the case of an artistic piece, performance can be evaluated, in a non-exhaustive way, by its behavioral richness in line with the theme, the originality of created actions or its aesthetic value (perceptual judgments). With regard to conversation, the purpose of the task is slightly different, and other performance markers should be used (e.g., quality of exchanges and information retained; interaction time; psychological factors such as affiliation, feeling of connectedness or interpersonal rapport). All these performance markers must thus be taken into account in the definition of motor signatures by correlating movement features to be extracted with these markers.

(iii) *Playing with the set of constraints* (*individual, task, environmental*) *to directly test their effects on behaviors and learning*. We suggest juggling the various constraints to assess the extent to which improvisational skills are domain-specific or domain-general. For instance, by analyzing an individual in solo and duo situations to evaluate the effect of social environment or by changing the type of the task. Longitudinal studies in a modified or unchanged environment, still lacking in the literature, can also be conducted to investigate more deeply the learning process and identify the various stages underlying the construction of improvisation skills.

AUTHOR CONTRIBUTIONS

AC conceptualized the perspective piece and wrote the first draft of the manuscript. BB and LM revised the manuscript and supervised the whole process. All authors approved the final version of the manuscript.

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On the Education About/of Radical Embodied Cognition

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In mainstream or strong university education, the teacher selects and transmits knowledge and skills that students are to acquire and reproduce. Many researchers of radical embodied cognitive science still adhere to this way of teaching, even though this prescriptive pedagogy deeply contrasts with the theoretical underpinnings of their science. In this paper, we search for alternative ways of teaching that are more aligned with the central non-prescriptive and non-representational tenets of radical embodied cognitive science. To this end, we discuss recent views on education by Tim Ingold and Gert Biesta, which are based on Dewey's philosophy of pragmatism and Gibsons' ecological approach. The paper starts by introducing radical embodied cognitive science, particularly as it relates to motor skill learning, one of our prime interests in research and teaching. Next, we provide a synopsis and critique of the still dominant prescriptive and explicating pedagogy of strong education. Following Ingold and Biesta, we search for a weak alternative through a careful consideration of the education of attention and the participating teacher. To illustrate our arguments, we use examples of the first author's teaching about/of motor skill learning. The paper is concluded by briefly considering the implications of weak education for a radical embodied science of motor skill learning.

Keywords: education, motor learning, radical embodied cognition, pedagogy, ecological psychology

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> *"Seek the truth and you will not find it, knock at its door and it will not open to you, but that search will serve you in learning to do."*
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> Rancière (1991/2007, p. 138)

INTRODUCTION

This paper addresses a contradictory practice among researchers of radical embodied cognition; in our teaching *about* radical embodied cognition, many of us tend to rely on the prescriptive and explicating pedagogy that squarely belongs to traditional cognitive science. On reflection, this makes us feel somewhat uneasy. Our current aim, therefore, is to search ways for the teaching *of* radical embodied cognition that are more aligned to the central non-prescriptive and non-representational tenets of radical embodied cognitive science. To this end, we discuss recent views on education as developed by Tim Ingold and Gert Biesta, among others. In particular, the thinking of Ingold, which is obviously inspired by Dewey's philosophy of pragmatism and Gibson's ecological approach, is of major influence. In fact, the current paper can also be read as an appraisal of Ingold's (2018) latest, stimulating book *Anthropology and/as education*. Before addressing these perspectives on education, we first introduce radical embodied cognitive science, particularly as it relates to motor skill learning, one of our prime interests in research and teaching. Next, we provide a synopsis and critique of the still dominant prescriptive and explicating pedagogy of strong education. Following Ingold and Biesta, we then search for a weak alternative, and in so doing, we closely consider the education of attention and the participating teacher. The paper is concluded by briefly feeding some of these ideas back into a radical embodied science of motor skill learning.

PROLOGUE: MOTOR SKILL LEARNING

Although there are several articulations of radical embodied cognitive science (Thelen and Smith, 1994; Chemero, 2009; Rowlands, 2010; Barret, 2011; Hutto and Myin, 2012; Malafouris, 2013; Gallagher, 2017), they do share the claim that human skill and learning are best understood on the scale of the relationship between a person and the environment. This strongly contrasts with traditional cognitive science that seeks to explain skill and learning by focusing almost exclusively on the person, citing internal computation and representation as causal determinants. For motor skills, these internally stored representations have been referred to as motor programs (Keele, 1968), schemas (Schmidt, 1975), and codes (Prinz, 1997), among others (see Summers and Anson, 2009). In general, a motor representation consists of a set of rules or procedures that specify—in different degrees of detail—and causally underpin the sequence of movements that form the motor skill. The representations form with practice. Fitts and Posner (1967, pp. 10–11), for example, conceived motor skill learning as the conscious assembling, structuring, and sophistication of rules (or subroutines) that get consolidated into an overall internal program. This internalization of rules releases the need for conscious control, and hence, skilled performance becomes increasingly autonomous. In other words, in traditional cognitive science, skill learning is principally about acquiring—literally, that is—internal representations (Araújo and Davids, 2011). It stands to reason that within traditional cognitive science teaching (motor), skills involve introducing the learner to the most appropriate set of rules. This has resulted in a pedagogy that is largely prescriptive (e.g., Brass et al., 2017). Practice serves to acquire the rules that are later internalized in motor representations and the teacher is the main source of information for these rules. Instruction, feedback, and modeling are used, first, to deliver the learner knowledge about the desired, ideal movement sequence of pattern, and second, to weed out any remaining aberrations from the desired movement. Accordingly, teaching is prescriptive, the "stilling in" (Ingold, 2018) of an ideal movement pattern, that is, ideal to the mind of the teacher.

Dreyfus (1992, 2008) and Dreyfus and Dreyfus (1986) criticized prescriptive skill learning theories. In particular, Dreyfus argued against the idea that instructing, feeding back, and modeling about the desired movement pattern are a precursor to the internalization of rules in a motor representation. By contrast, skill learning requires that learners, if they are to achieve higher levels of competence, must cease using the movement rules, rather than internalize them. According to Dreyfus, positing that learning involves the acquisition of internal representations is "like claiming that since we need training wheels when learning how to ride a bicycle, we must now be using invisible training wheels whenever we ride. There is no reason to think that the rules that play a role in the *acquisition* of skill play a role in its later *application*" (Dreyfus, 1992, p. xiii, italics in original). Dreyfus does not deny that instruction, feedback, and modeling play a pertinent role in skill learning. Yet, rather than being prescriptive and allowing the accumulation of knowledge about the ideal movement sequence or pattern, they serve to allow the "accumulation of experience." That is, instruction, feedback, and modeling permit a learner to practice, such as training wheels allow a child to find out how to propel and steer the bike (Dreyfus and Dreyfus, 1986, p. 22). These ideas strongly resonate in current radical embodied cognitive science, especially within the ecological approach to (motor) skill learning (e.g., Thelen and Smith, 1994; Chemero, 2009; Newell and Ranganathan, 2010; Davids et al., 2012; Chow et al., 2016; Orth et al., 2017).

In a nutshell, within the ecological approach, skill and learning are explained without recourse to internal computation or representation (Gibson, 1966, 1979). Instead, the dynamic person-environment relationship is primary, and skill learning is understood as an increasingly improved fit between the person and the environment (Davids et al., 2012). Skill learning is not uniquely determined by personal constraints, but always in unison with environmental and task constraints (Newell, 1986). In a sense, the ecological approach holds that (new) skills *emerge* rather than that they are *acquired*. Instruction, feedback, and modeling add to the constraints under which (new) movement patterns emerge (Newell and Ranganathan, 2010; Chow et al., 2016). They have no logical priority, but function in concert with other constraints to increase adaptability of the movement patterns. Similar to other variations in constraint, instruction and the like prompt a learner to search different movement patterns to satisfy the constraints. This is associated with a (nonlinear) pedagogy that is emphatically non-prescriptive (Chow et al., 2016): rather, it points the learner to the informational richness of the situation (i.e., metastable regions), allowing new movement patterns to arise or new action opportunities (i.e., affordances) to be discovered. This is what Gibson (1966) referred to as the "education of attention."

Proponents of the ecological approach are radical in their commitment to a pedagogy that is non-prescriptive. For example, Davids et al. (2012, p. 117) maintained that "it is futile to try and identify a common, idealized motor pattern towards which all learners should aspire (e.g., learning a 'classical' technique for an action)." Indeed, we are very sympathetic to that commitment in our science (e.g., van der Kamp et al., 2003; van der Kamp and Renshaw, 2015; Orth et al., 2017, 2019). Nonetheless, do we truly practice what we preach? It appears to us that, ironically, in teaching *about* radical embodied cognitive science, we often rely on the prescriptive pedagogy that we strive to avoid in our research in motor skill learning.

THE OMNIPRESENCE OF STRONG EDUCATION

The great American educationalist, theorist, and philosopher John Dewey[1] characterized traditional education as a business of transmission, where knowledge and skills that have been worked out in the past are being imposed on a new generation (Dewey, 1938/2015, pp. 17–18). Accordingly, in this traditional or strong education (Biesta, 2013, 2017), the teacher is an omniscient authority who selects and communicates knowledge and skills that students are to acquire, and—supposedly—use *after* they have finished school and/or university in everyday (working) life. The teacher *prescribes* and *explicates*. To paraphrase an example of Ingold (2018, p. 4), the teacher chooses the subject matter and encodes it in some form or package that allows it to be delivered to the students with minimal distortion. The students, after unpackaging it, should then—ideally—have acquired the exact same knowledge as the teacher began with. In other words, the teacher "fills" the students with knowledge content, which they receive, rehearse, and memorize. The teacher instructs, and the students learn. Freire (2008), a radical Brazilian educational theorist and founder of critical pedagogy, refers to this prescriptive pedagogy as banking education: "Education thus becomes an act of depositing, in which the students are depositories and the teacher is the depositor" (p. 244).

Today, despite a long record of vibrant opposition (e.g., Dewey, 1938/2015; Illich, 1970/2019; Rancière, 1991/2007), this is likely still how most university teachers typically teach, knowingly and unknowingly (see, e.g., Biesta, 2006, 2017). In fact, to make the prescriptive pedagogy more effective—at least according to educational managers—teachers increasingly are to adhere to principles of constructive alignment (Biggs and Tang, 2011). Teachers (are told to) describe the intended learning outcomes, and devise teaching methods, students' learning activities, and assessment tasks to directly address the intended learning outcomes. For example, one of us (John) coordinates and teaches a course that addresses motor skill learning. The course, called *Perceptual-motor learning*, is an elective within the 1-year master of science program *Human Movement Science: Sport, Exercise and Health*[2]. Each year, approximately 50–60 students take the course. As the teacher, John defines (or confirms) the intended learning outcomes[3], chooses course content, teaching and learning activities, and assessment methods. Broadly speaking, John aims to prepare students to advance theory and research on motor skill learning and apply them to societal problems. To this end, students must acquire knowledge and be able to critically evaluate current theories (including not only ecological psychology, but also more traditional cognitive approaches such as schema-theory and common coding theory), methods, and results of research. John uses a compendium of classical and current scientific papers and book chapters, the contents of which are assessed in a written exam. The course is organized in lectures and tutorials. In the lectures, John uses the compulsory literature to explicate and structure the different theories and the associated research methods—by and large, John does the talking, the students listen and make notes (hopefully). In subsequent tutorials, the students present and discuss cases from the practices of sport, rehabilitation, and physical education and thus apply theory and research results to societal problems, putting them into context. As an assessment, students produce a knowledge clip in which they elaborate one case. (The times they are changing, formerly they wrote an essay.) During the tutorials, students are meant to do the talking and thinking, but John often finds himself interrupting discussions to correct—in his view—misapprehensions of theory and methods or to further explicate. In short, despite good intentions, John's teaching is largely prescriptive, and as such shares many features of strong education[4]. As a teacher, John makes all the choices without consulting prospective students, though he does consider the suggestions made by students in the previous year's course evaluations. By and large, students have no say in course content, it is enforced upon them and they have to adapt to it (cf. Freire, 2008). This being said, students are invited to the lectures and tutorials; attendance is not mandatory; yet, they show up in high numbers, except when exams are approaching. Also, students do value the course and teaching highly, giving ratings of quality of course content, lectures, and tutorial of approximately 4.5 on a 5-point scale.

It is good to pause. The students' high appreciation may merely reflect theirs and John's adaptation to banking education. Yet, according to Freire (2008):

> Implicit in the banking concept is the assumption of a dichotomy between human beings and the world: a [student] is merely *in* the world, not *with* the world or with others; the [student] is a spectator, not re-creator. In this view, the [student] is not a conscious being (*corpo consciente*); he or she is rather the possessor of *a* consciousness; an empty "mind" passively open to the reception of deposits of reality from the world outside (p. 247; italics in original).

In other words, the assumptions underlying John's teaching—as presumably that of many colleagues—deeply conflict with the assumptions underpinning his science. Even though he emphatically tries to show students that radical embodied cognitive science deserves careful consideration, John does so

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[1] Interestingly, Dewey was also interested in motor skills. In a paper on the reflex-arc, he argued strongly against, very much in spirit with current radical embodied cognition, the hypothesis of an independent "agency in the center of the soul" (or central idea) or a "superior force in the stimulus" as the cause of a motor response (Dewey, 1896, p. 364). Both Chemero (2009) and Gallagher (2017) identify Dewey as one of the forbearers of radical embodied cognitive science, while Lobo et al. (2018) discuss Dewey's direct influence on ecological psychology.

[2] https://www.vu.nl/nl/studiegids/2018-2019/master/g-j/human-movement-sciences/index.aspx?view=module&origin=51003848&id=50044209

[3] In fact, John has no complete freedom in defining the intended learning outcomes. They must fit within the program objectives and exit qualifications.

[4] To John's immediate defense, an increasingly important part in the course is the practical, during which students practice a new motor skill. It is deliberately less prescriptive and explicative. We turn to that below.

by regulating the way in which they encounter it. John merely deposits it upon the students. As Ingold (2018) argues: "Insofar as such training moulds the raw material of immature humans to pre-existent design, while it might replicate the design, it serves no educational purpose whatsoever" (p. 5). This conclusion may be considered a little too sweeping, but there are good reasons to be critical toward strong education.

First, as Biesta (2013, 2017) argues, strong education overemphasizes the qualification function of education. Qualification provides students with the specific knowledge and skills needed for life after school or university, typically a particular job or profession; yet, socialization and subjectification are equally important functions of education. With socialization, students are introduced in existing ways of doing of particular groups or cultures, while with subjectification, students become autonomous and independent individuals. The one-sided bias toward qualification in strong education, presumably because it offers teachers (and managers) a high certainty about students' learning outcomes, threatens to eradicate the socialization and subjectification functions. Instead, Biesta advocates weak education, in which the mutual interdependency of qualification, socialization, and subjectification is not only recognized but fostered, despite learning outcomes becoming less predictable. A pedagogy that solely consists of prescription and explication cannot achieve this.

A second problem with strong education was recognized by Reed (1996), who was the first to consider social institutions such as work and school from the perspective of ecological psychology. Reed was profoundly influenced by the writings of Dewey. He argued that in mainstream education, the understanding of the world that students acquire is based on secondhand experience, in which knowledge is selected, modified, packaged, and presented by teachers. That is, in schools and universities, the world is not experienced firsthand, but always through (scientific) representations of the world that are construed by others. Yet, "reading cookbooks is not the same as cooking" (Reed, 1996, p. 108). Consequently, Reed emphatically calls for an education that better balances firsthand and secondhand experience. Instead of depositing knowledge from outside, education must provide students with opportunities to actively see, feel, taste, hear, or smell the world for themselves.

We are back to square one. How can we offer such a non-prescriptive, weak education?

THE EDUCATION OF ATTENTION

> Education, I argue, is not a "stilling in," but a "leading out," which opens paths of intellectual growth and discovery without predetermined outcomes or fixed end-points. It is about attending to things, rather than acquiring the knowledge that absolves us of the need to do so; about exposure rather than immunization. The task of the educator, then, is not to explicate knowledge […] but to provide inspiration, guidance, and criticism in the exemplary pursuit of truth (Ingold, 2018, p. ix).

This extended quote is from *Anthropology and/as education* by the social anthropologist Tim Ingold. According to Ingold, knowledge and skills cannot be isolated from life experiences (see also Dewey, 1938/2015). It is not only a thinking in the head. Instead, education is necessarily intertwined with experience—firsthand experience, that is (Reed, 1996). Ingold advocates a way of education in which students learn to attend and respond to what is going on in the world. Like the way craftspeople obtain knowledge in their engagements with materials when making artifacts. Ingold takes this literally. He narrates an occasion where he takes a class of students to the beach to weave baskets out of willow (Ingold, 2013, pp. 22–24). We are told that students first stuck willows vertically in the sand to form a frame, and then alternately weaved other pieces horizontally in and out the vertical frame, and so gradually formed an inverted cone. Ingold recounts that students were surprised by how unmanageable the willows were, sometimes even springing back and scratching arms and face. Yet, the difficulty with which they bent, also held the construction together once they were in place. The basket's precise shape proved difficult to impose. In the end, each basket turned out in a different shape, uniquely reflecting, according to Ingold, the relations between the willow and the weaver. For example, the height of the basket was related to the weaver's body length, because weaving the sturdy willows required engagement of the whole body. Also, the strong wind bended the vertical frame, causing the baskets to be curved to one side, depending on how close they were to the shore. Students were proud with the baskets they had made. They told that "they had learned more from one afternoon than from any number of lectures and readings: above all about what it means to make things, about how form arises through movement, and about dynamic properties of materials" (Ingold, 2013, p. 24).

Rather than transmitting or depositing knowledge in the mind of students, Ingold invites his students to truly experience firsthand, to do undergoing. Although this experience may also help students increase their knowledge *about* matter and form, and indeed is likely to do so, the main purpose is to promote students' knowledge *of* making, basketry in this case. According to Dewey (1938/2015), the continuity of these experiences is the gist of education. Every experience, every doing undergoing requires a student to actively attend and respond to the environment, or, as Ingold (2013, 2018) phrases it, to *correspond with the world*. A continuity of experiences transforms the student, affects subsequent experiences, and opens up new environments (Dewey, 1938/2015, p. 37). In this respect, education is (also) about becoming attentive and responsive (i.e., response-able) to the world (Reed, 1996; Ingold, 2001, 2018; Masschelein, 2010). It is here that Ingold refers to the *education of attention*.

It was Gibson (1966), the originator of ecological psychology, who introduced the concept of education of attention in the context of perceptual learning. Gibson argued that, with practice, an individual comes to "orient more exactly, listen more carefully, touch more acutely, smell and taste more precisely, and look more perceptively" (p. 51). In arguing for perceptual learning to be a greater noticing of differences (cf. Dreyfus, 2008), Gibson disputed traditional theories of perception, which conceived perceptual learning as a process of enrichment. With enrichment, perceptual learning unfolds by acquiring increasingly refined representations that add meaning to sensory stimulation. Interestingly, as Gibson and Gibson (1955, p. 34) noted, enrichment theories thus hold that "perception is progressively in *decreasing correspondence with stimulation*." In contrast, Gibson and Gibson claimed that perceptual learning is better characterized as an increasingly differentiated responsiveness to the environment, resulting from a greater correspondence with stimulation or information.

Gibson (1966, 1979) only provided us with a minute description of the education of attention[5]. Arguably, the most elaborate interpretation has been provided by Michaels and Carello (1981) and also see Ingold (2001), although it also has been expanded upon by developmental psychologists who typically refer to it as differentiation (e.g., Adolph, 2000; Gibson and Pick, 2000). Michaels and Carello capture attention as the control of the detection or pickup of information. Attention thus helps explain that different individuals or an individual at different times has a variety of perceptions; they pick up different information. It is not that representations show different activation patterns or that stimuli are processed differently, rather different information is attended to. Attention is embedded in exploratory activity, during which the individual actively searches the environment, allowing an individual to control the information that is detected. It reveals the affordances of the situation, that is, the opportunities that the environment offers the individual. Perceptual learning then becomes the education of attention: a progressive change in the control of the detection of information that correlate with the affordances of the environment. In this respect, learning does not result in an individual who has acquired new knowledge, but in an individual who inhabits a richer landscape of affordances (Rietveld and Kiverstein, 2014, see also Dreyfus, 2008). As such, "the education of attention can manifest itself in many ways. The domain covered by the phrase *education of attention* is far broader than what has been called *perceptual learning*. Indeed, we would claim that all learning can be understood as the education of attention" (Michaels and Carello, 1981, p. 81).

To educate attention thus makes experience possible; it invites students to do undergoing, perhaps revealing new affordances. Although in this opening up to the world, the searching is deliberate, what will be revealed—if anything—is not known beforehand. It is the active, inquiring, expanding experiencing that counts, not the particular content or outcome of the experience (Reed, 1996). In contrast to the prescriptive pedagogy of strong education, weak education always entails a degree of uncertainty for students in their encounters with the world. In the words of Masschelein (2010; see also Biesta, 2013), it

> "invites [the student] to go outside into the world, to expose oneself, i.e., to put [her]self in an uncomfortable, weak position, and it offers the means and support to do so. I think that it offers means for experience (instead of explanations, interpretations, justifications, representations, stories, criteria, etc.), means to become attentive. These are poor means, means, which are insufficient, defective, which lack signification, do not refer to a goal or an end."

Seemingly, this is what Ingold (2013) intended, when inviting his students to the beach for basketry, and that is what John had in mind when introducing the practical into the *Perceptual-motor learning* course, asking his students to practice a new skill. Not merely to put theory into context, but to attempt to educate the students' attention toward …, who knows what?

In this practical, students practice one new skill of their own choice, 5 min every day over a 5-week period spanning the entire course. Students practice juggling, knitting, whistling their fingers, performing hand stand, rolling a coin across their knuckles, playing the ukulele, and many other skills. Along the way, they actively explore the affordances of skill learning: they move, imitate, try, expose themselves to errors, repeat, feel, correct, take risks, get energized, quit, plan, reflect, vary practices, think, get bored, frustrated, are proud, notice and adapt; in short, they do undergoing learning, become attentive to increasingly differentiated aspects of learning. After 5 weeks, the practical is concluded with a collective skill demonstration event. This event is merely for fun and to reflect on their practice, because it is the experience of practicing that counts, not the learning outcome. The practical is not entirely noncommittal, though. John verifies that students do undergoing by placing attentional pointers along the way (cf. Rancière, 1991/2007). These pointers are not prescriptive, but meant to initiate and continue the education of attention. They include a brief introductory lecture and weekly questionnaires, which aim to educate attention to how key theoretical concepts cognate (or not) with their practice (e.g., variability of practice, self-efficacy, modeling, degeneracy, accumulation of declarative knowledge). Actually, students suggested using vlogs instead,[6] and hence, students now produce weekly vlogs demonstrating and reflecting on their practicing against the backdrop of a concept of their own choice. The vlogs are shared on a (protected) course website. There is a thin line between students who genuinely open up and attend and respond to how practice unfolds, and students, who, in the vlog, mostly reproduce their knowledge about the concept and use practice to exemplify. Interestingly, at the start, there is widespread enthusiasm among the students. Yet, students value the practical less than the orthodox lecturing, with ratings being consistently below 4.0. The large standard deviations perhaps indicate that some students find it difficult to handle the openness of the learning aims and/or are simply fed up with practicing after 5 weeks.

The practical is introduced by presenting the experience of Ingold's (2013) class with basketry, emphasizing that the practical is about experiencing motor skill practice and learning firsthand.

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[5] In his 1979 book, education of attention did not even make the subject index. Perhaps, Gibson only meant his readers to become attentive of it.

[6] John had asked a group of students, who had finished the *Perceptual-motor learning* course, to make a proposal for revising the course. The students did this as part of an assignment to acquire a qualification for teaching in higher education. This turned out be very fruitful and inspiring. Another way to give the students a bigger say in the course contents would be to solicit their aspirations before the start of the course.

Students are made aware that attending and responding can generate knowledge, but also that this does not happen necessarily. In this respect, many students experience something akin to Bernstein's (1967) concept of context-conditioned variability, but on a longer learning timescale. With context-conditioned variability, Bernstein voiced that the correspondence between an executive motor command and the movement depends on the context. The context is never completely fixed, but inherently variable, and further to this point, each movement changes its own context (Turvey et al., 1982; Turvey and Fonseca, 2009). Consequently, an actor cannot achieve an intended movement by generating the necessary motor command(s), because they are insensitive to the ongoing conditions. Analogously, in the practical, most students start by searching the Internet, especially YouTube, to locate tutorials that explicate and demonstrate rules about how the to-be-learned skill is to be performed, or occasionally, how it is to be practiced.[7] Indeed, students experience following and emulating these rules as helpful, particularly to kickstart learning. However, like an executive motor command producing the movement, the tutorial instructions are largely ignorant to an individual student's learning conditions. Accordingly, at some point, students' attention will be drawn (or not) to the need to seek context-conditioned adaptions to further the new skill. Their attention will be educated to the need for an increasingly differentiated responsiveness, the exact nature of which they can hardly put into words, nor is it to be found in YouTube tutorials. For example, one student accumulated detailed knowledge *about* whistling with her fingers, among others, by using split screen to imitate and compare her own performance with a master model: "I am a bit stuck, and do not master whistling yet. […] I hope to see where I go wrong, because I keep level on the same thing, not being able to fully master; yet, I have no idea yet, but I hope it works." Likely, however, her knowledge about the whistling skill was not the limiting constraint, since during the skill demonstration, her description of the rules sufficed for a fellow student to whistle almost instantaneously. Yet, the student herself found it hard to make any progress. That is, until she construed from the concept of degeneracy (Lee et al., 2014) that instead of perfecting her whistling technique, she better would start "experimenting all kinds of different manners, to find a solution that works for me, suits me best. By changing movement solutions, I was able to find a solution that worked for me, and now I am actually able to, *kind of*, whistle."

Despite her hesitance to go beyond the certainty of explicit knowledge, the continuing failure afforded the student to start to improvise: that is, to stop using rules and accumulate differentiated experience instead (Dreyfus, 2008). Admittedly, her final performance was still best captured as hissing, but that is not the point. Over the years, the practical has afforded students this and many other firsthand experiences of motor skill learning. The content of these experiences is of less importance, what matters is that students attend to the landscape that the practical affords, that they attentively follow and respond to what happens during practice. This opening up, however, can neither be planned nor controlled:

> "The aim in [practice][8] is not to test a preconceived hypothesis but to open a path and follow wherever it may take you. It is not so much iterative as itinerant: a journey undertaken rather than a cycle of returns on a fixed point. It works more by intuition than by reason; opening from within rather than penetrating from without. It is prospective rather than confirmatory. The patience of [practice], in this sense, lies in the dynamics of attention, and in the endurance of waiting. We have to allow things to come into presence, in their own time: they cannot be forced." (Ingold, 2018, p. 41)

THE PARTICIPATING TEACHER

The teacher evidently has a role to play in educating students' attention. Weak education does not imply the end of teaching or that an ignorant teacher would suffice (cf. Rancière, 1991/2007). Then what is the teacher's role? One influential suggestion is that the teacher should act as a facilitator, scaffolding the learning process and creating environments that provide learning opportunities. This is the perspective of constructivism (Palincsar, 1998; Richardson, 2003). Basically, constructivism is a theory of learning, not teaching. Although many perspectives proffer, two main accounts can be distinguished (Palincsar, 1998). The cognitive or Piagetian account holds that students actively construct new understandings, learn by actively merging previously acquired knowledge with new information. Learning, then, is largely an individual process, occurring within the student and resulting in cognitive structures. In the sociocultural or Vygotskyan account, knowledge is co-constructed in collaborative activities with others, emphasizing that learning is primarily a social activity. Consequently, in constructivism, a teacher's role is not to transmit knowledge, but rather to offer opportunities for students to create their own new knowledge, preferably in collaborative activities (i.e., iterative cycles of interaction, negotiation, and collaboration). For example, a teacher can facilitate a debate of ideas, in which students discuss a topic with the purpose to achieve a shared understanding. The teacher can enrich the debate with video-material, but does not herself participate in the discussion (Koekoek et al., 2019).

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[7] In this respect, the introduction of the Internet has greatly affected how people learn new motor skills. For researchers, there is a wealth of issues to be addressed on how Internet shapes (self-controlled) motor learning. For example, as one reviewer noticed, the YouTube tutorials need not necessarily function to prescribe movement rules, but may also function as an initial reduction in the degrees of freedom, helping the students to begin practice (see also Dreyfus, 1992).

[8] In this quote, Ingold describes patient experimentation, instead of practice. Patient experimentation is contrasted with the scientific method in major science, in which knowledge is acquired from carefully planned and controlled experiments in which theory-derived hypotheses are tested. Typically, the observations and measurements in the experiment result in the refinement (and sometimes rejection) of the hypotheses, which are further tested in a subsequent experiment and so on.

Some constructivists, particularly among those who adhere to the cognitive account, tend toward invoking a minimum role for the teacher, that is, only as a promotor of co-construction rather than as a participant (cf. Stetsenko, 2017). Biesta (2013), following Dewey, refers to this practice as *learning*, which he distinguishes from *education*. In education, both students and teacher must participate, and attend and respond to each other. Education only occurs if the activities of students and teacher mutually influence each other, open up to each other. Both sides must share a stake in the outcome and be willing to transform their ideas, understanding, and emotions. Accordingly, teachers must also be willing to expand their experiences. This can be uneasy and disturbing, but it is essential of weak education that the teacher is also present and is prepared to put what he or she has, indeed what he or she is, "on the table" (Ingold, 2018, p. 52). In fact, Biesta (2013) asserts that the teacher, in doing so, can add something that goes critically beyond what students can achieve on their own. This is the gift of teaching, but only when the students receive it as such. The gift of teaching is not something that *is*, but something that *makes a difference*[9] (Biesta, 2013, p. 85). It is a shared experience, perhaps in the form of making a critical or supportive remark, or posing a question, exchanging ideas, by offering guidance or inspiration, or by setting an example. It is distinctive of weak education, however, that the teacher cannot plan this gift, because planning (prescribing) it would annihilate the uncertainty that is necessary for it to be received as a gift. This is the beautiful risk of education (Biesta, 2013). All the teacher can do is expose him- or herself, and wait, the gift cannot be forced upon the student.

These are big words. The ongoings in the practical are more modest. John does himself participate. Over the years, he did practice, both successfully and in vain, silly walks, the *kendama*, a three-ball cascade in juggling, the handstand, and unicycling. John shares his practice experiences with his students, also by recording his own, fairly clumsy vlogs. This is not a process of transmission, but one of attending and responding. Also, students have stories to tell. For John, and presumably for students alike, this mutual attending and responding occasionally has pointed to alternative ways of practicing offering new perspectives of learning. Probably the most conspicuous is the emotion of learning, also because it has been underplayed in contemporary theories of motor skill learning, including theories of radical embodied cognition (for exceptions, see Colombetti, 2014; Headrick et al., 2015; Withagen, 2018). Yet, motor skill learning is circularly constrained by or nested within emotions and moods (Balagué et al., 2019). Nonetheless, researchers in motor skill learning often oversee or suppress emotion from their studies; if anything, the typical participant in an experiment is feeling uninterested. When trying to imitate John Cleese's silly walks, John started practicing at home in the living room. Yet, after the first few successful strides, John quickly discovered that to further progress, more space was needed, which was only to be found outside, in the cold evenings, after dark. It was the only way to avoid the embarrassment of walking into one of the neighbors—almost. Commitment to practice quickly dropped and excuses to skip the day's practice were easily found. Also, students did often suggest that feelings of commitment can positively energize and facilitate investment in practice, stimulate improvisation and/or variability during practice, and make it easy to ask important others for feedback. Nonetheless, feelings of commitment can (suddenly) give away to feelings of monotony or even avoidance, resulting in solitary, routine-like repetitive practice. Indeed, the emotion of learning may be intimately connected with accelerations and arrests in learning, respectively. But not entirely. Arrests in learning can also go together with feelings of anxiousness. John, for example, got stuck after successfully throwing and catching one and two balls while attempting to master juggling. Intriguingly, while this may seem easy enough, it felt frighteningly difficult to throw the third ball. Possibly, John was overthinking and monitoring too many rules and worried too much to risk the uncontrollable (i.e., throwing the third ball would surely mean dropping them all). In the end, merely concentrating on the rhythm of the throws, however, did do the job. It turned attention to Dreyfus' proposition that if one keeps on seeking the safety of rules, learning will not progress (Dreyfus and Dreyfus, 1986; Dreyfus, 1992). Taking risks of failure and ceasing to use rules may go together with strong feelings of anxiety, just like succeeding can be deeply rewarding, as John can attest. Dreyfus is now mandatory reading in the course (no pun intended).

EPILOGUE: MOTOR SKILL EDUCATION

We have advocated weak education as way of teaching that is more in line with radical embodied cognitive science, and thus ecological psychology, than the widely accepted prescriptive and explicating pedagogy that characterizes strong education. In particular, we have pointed toward the necessity of educating students' attention and the actively participating teacher to bring about a weak pedagogy. To wrap up this paper, we briefly consider the significance of weak education for a radical embodied cognitive science of motor skill learning.

A pertinent implication of weak education is that research into motor skill learning should much more emphatically address values wider than the current narrow focus on the "technics" of motor skill learning, such as the ongoing emphasis on optimizing training interventions and performance monitoring changes (Farrow and Robertson, 2017). We are not arguing that this is undesirable, but in sports, physical education, and rehabilitation, however, motor learning typically has fulfillments that go beyond qualification *per se*. For example, athletes invest many hours of practice to achieve distant goals, and in so doing, learn to persevere also when there is no immediate gratification (i.e., subjectification). Or, students discover ways of doing in sports or dance cultures they would not have encountered without physical education

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[9] This is too nice not to mention. In German "to make a difference" is "schillen" and in Dutch it is "verschillen." Ingold (2018, p. 42) explains that the English "skill" originated from "schillen" (Ingold, 2018, p. 42). Accordingly, the gift of teaching is something that creates skill.

(i.e., socialization). In this respect, it seems appropriate to refer to motor skill *education*, rather than learning.

Motor skill education would, among others, promote expanding firsthand experience, emphasizing the accumulation of experience instead of knowledge (Dreyfus, 2008). It would challenge individuals to actively explore the "unknown" by exposing them to situations where new affordances can be created and discovered (see Dicks et al., 2017; Walinga et al., 2018). Individuals are not trained to adopt ideal movement patterns (or, for that matter, ideal gaze patterns), but they are brought into (variable) practice conditions in which numerous adaptive actions can emerge—if they feel sufficiently safe to explore. Secondly, and crucially, motor skill *education* would also strongly encourage a participating or co-adapting teacher (or coach or physiotherapist) to create opportunities for shared experiences with the learner. For example, we have recently argued that motor skill learning in sports is best captured as a process that is distributed across the athlete and the coach (Orth et al., 2019), in which athlete and coach mutually constrain each other. For instance, the coach must closely monitor variations in an athlete's actions and emotions during practice, which can signal emerging changes in skill (Headrick et al., 2015). A coach shapes the practice conditions to enable this change. Yet, the change can never be fully orchestrated by the coach, not in the least, because the coach's actions and emotions themselves co-constitute the practice conditions. This limited certainty and controllability in the mutual attending and responding between athlete and coach in particular affords new and creative actions. It is exactly for this reason that we should cherish weak education, both in motor skill education itself and in the education of motor skill education.

AUTHOR CONTRIBUTIONS

JK, RW, and DO contributed to the conceptualization and background research. JK drafted the first version of the paper and finalized the paper. RW and DO made critical revisions to the first draft.

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CONCEPTUAL ANALYSIS
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Skill Training Periodization in "Specialist" Sports Coaching—An Introduction of the "PoST" Framework for Skill Development

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Across sports and movement science, training periodization has been recognized as key for athlete development and performance. While periodization with regard to physiology has a proven history, the structuring and periodization of motor learning and skill development is seemingly less researched and practiced. Despite the existence of numerous theoretical accounts underpinning skill acquisition training and more recently emerging periodization models, a cohesive framework to practically support coaches in the context of "specialist coaching" appears to be needed. The use of "specialist coaches" for individualized, one-on-one or small group trainings displays a growing trend in team ball sports. Despite limiting the replication of game-representative environments (i.e., by constraining the number of involved athletes in training), "specialist coaches" in performance sport constantly aim to achieve marginal gains and refinements in athlete development. In order to support these "specialist coaches" and fill a research gap on skill training periodization, the current paper seeks to review and transfer contemporary skill acquisition training theory (driven by the constraints-led approach) into a practically-applicable "Periodization of Skill Training" framework ("PoST" framework). This framework provides valuable conceptual and practical support for "specialist coaches" in performance sport; which will in turn, enhance, and refine adaptive movement variability for sport skills and manipulate skill training environments (i.e., over the course of macro- and micro-cycles, and for the planning of single training sessions). Practical examples from soccer goalkeeping (i.e., a "specialist coaching" context, often constrained to a small number of players in the training environment) will underline the proposed framework.

Keywords: specialist coaching, skill acquisition training, motor learning, constraints-led approach, movement adaptability, representative training, soccer goalkeeping

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INTRODUCTION

Across team sports, it is commonly recognized that organized training activities (led by coaches) enhance athlete development and better prepare performers for the dynamic demands of competition environments (Hodges and Franks, 2002; Côté et al., 2007). These training activities, usually in the form of "team training" (e.g., 22 players in a soccer training session), are acknowledged to be most effective for skill acquisition and refinement when replicating the complex interacting constraints that are representative of performance environments (Davids et al., 2008; Renshaw et al., 2019a). Yet, in order to achieve marginal gains when developing athletes, there is a growing trend in performance sport for the use of "specialist coaches" for individualized one-on-one or small group trainings (Smith, 2018). The involvement of "specialist coaches" has been common practice in sports like American football, basketball and rugby for years; however, specialized coaching positions in soccer, such as a "striker coach," "throw-in coach," "rehab coach," or "individual development coach," have only more recently emerged (e.g., BBC, 2018; Smith, 2018; Austin, 2019). Given the prominence of the "specialist coaches" trend, supporting them with up-to-date scientific principles on skill training planning appears to be important. The involvement of a limited number of athletes often proves to be a constraint in "specialist coaching" training environments, and so the challenge of full representation of the performance demands may be denied. Thus, informational constraints in these training environments may not invite exploration of action opportunities. Following this limitation, and driven by anecdotal evidence and abiding scientific concerns about the coaches' choice of training activities, we aim to circumvent the risk of "specialist coaches" moving toward "traditional" coaching methods. These "traditional" coaching approaches are often based on intuition (Williams and Ford, 2009), "folk pedagogies" (Harvey et al., 2013), and/or have historical precedence (Williams and Hodges, 2005). In detail, several features may be displayed by "traditional" coaching: (1) limited performance uncertainty and variability of actions (Passos et al., 2008; Krause et al., 2019); (2) decontextualized movement coordination from the performance environment (Stolz and Pill, 2014); and (3) monotonous and repetitive technical drills in training (Renshaw et al., 2009; Krause et al., 2018).

Realizing concerns about the application of contemporary coaching approaches, we aim to meet recent calls from multiple directions for advancement in coaching practice. On the one hand, there is a need for "more engagement of researchers in supporting the application of theory into practice" (Renshaw et al., 2016, p. 475); and on the other hand, there has been recent demand for coaching practitioners to adopt research-supported coaching methodologies in order to systematically plan (and periodize) skill training (Correia et al., 2019; Renshaw and Chow, 2019). With the calls for more support from researchers in mind, there have been some attempts to look at the periodization of skill training; in particular, the Skill Acquisition Periodisation (SAP) framework by Farrow and Robertson (2017). The "SAP" framework was developed to measure and monitor longitudinal skill training in a high performance environment. These authors did a remarkable job at re-conceptualizing and relating physiology periodization principles to their "SAP" framework in order to help coaches understand the concepts more easily; for example, using existing and already-understood training physiology terms like specificity, progression, and overload. In addition, the "SAP" framework does an excellent job of separating aspects of the training environment (e.g., specificity or progression) and proposes measurements for these aspects. While many of these measurements are well-described in the 2017 paper, both sub-elite and elite performance sports coaches may struggle accessing relevant equipment, specialists, or having the time for the proposed measurements.

Farrow and Robertson's outlined strategies for longitudinal skill training of athletes in a high performance environment look to be particularly useful for team coaches that run full year or multi year programmes in preparation for international events. However, there are many situations (such as those experienced by a "specialist coach") where a practitioner will only work with an athlete for a single session or a short period of time; in such situations, longitudinal periodization is ultimately aimed for, but may not be possible given the constraints of the training environment (e.g., the time with the athlete). The "Periodization of Skill Training" framework (referred to as "PoST" framework) presented in this paper (see later) aims to integrate the skillful monitoring and measuring principles of the "SAP" model. In order to advance the field of skill acquisition training for those not in charge of whole teams, the proposed framework presents a model of skill development and refinement. This framework is especially targeted at "specialist coaches" working at the performance level with non-representative settings and very small athlete numbers.

Next to the "SAP" framework, a prominent framework for skill learning (and training periodization) is displayed by game-based approaches (GBAs); these, in large, describe "the use of modified and/or conditioned games" to holistically evolve game-intelligent performers (Kinnerk et al., 2018, p. 6). To date, numerous GBAs, such as the Teaching Games for Understanding (TGfU) Model or the Game Sense Model (GSM), have been proposed and applied to team sports contexts (see Kinnerk et al., 2018, and Stolz and Pill, 2014, for detailed reviews of various GBAs). In detail, GBAs are theoretically grounded on constructionist learning theory and discovery learning (Bruner, 1979), and originate from an educative-pedagogical perspective (Harvey et al., 2018). While highlighting a learner-centered approach (as opposed to a learner environment-centered approach in the constraints-led approach; Renshaw et al., 2016), GBAs consider a variety of playing forms (Pill, 2012, 2016); these forms include: "small-sided games" (i.e., "match-play with reduced number of players and two goals"; Ford et al., 2010, p. 487); and "conditioned games" (i.e., "small-sided games, but with variations to rules, goals or areas of play"; p. 487). Despite some theoretical distinctions to the constraints-led approach (see Renshaw et al., 2016; Harvey et al., 2018), we do applaud the contribution of GBAs for the modification of skill training for entire teams and large groups of athletes. However, regarding the context of "specialist coaching" with single athletes, applicability of the aforementioned playing forms and games is limited to team-based training approaches (see later).

Considering previous enriching conceptual work and its potential limitations, it remains important to further progress and translate academic knowledge in order to support coaches in their systematic planning of "real world" training sessions. Thus, we aim to provide theory-driven challenges and practically-applicable tools for coaches to systematically plan and adjust task constraints in individualized training with skilled athletes (see later); i.e., over multiple training months, weeks and for units within single training sessions. While widely-advocated theoretical groundwork is considered throughout this paper, we apply it to a newly emerging training context. In detail, we consider "specialist coaches" working on position-specific details with performance athletes (individually or in small groups). By proposing the "PoST" framework (grounded on ideas from the "SAP" model), we encourage practitioners to actively assess (1) individual athletes' skill levels and training stages; (2) the training environment based on the number of athletes involved; and (3) perceptual-cognitive and motor demands that athletes face in dynamic performance environments (i.e., the game). Finally, while the "PoST" framework and its (sub-) stages introduce the concept of "information complexity," it further supports a coaching practitioner focus by proposing approaches toward replicating (parts) of game-representative demands within session designs. These approaches are explored based on two critical conceptual questions: how can coaches adequately facilitate and periodize skill training environments (1) over the course of a macro-cycle and micro-cycle (i.e., the periodization of "specialist" training over the course of multiple months and sessions during 1 week of a season)? and (2) throughout a single training session (i.e., the structure of a single "specialist" training session with ∼1–4 athletes at the performance level)?

In an attempt to present contemporary theoretical insights, and apply these to the "PoST" framework for "specialist coaching," this paper is structured in three distinct parts: Part A, skill training theory and research, which provides a theoretical foundation for part B, "Periodization of Skill Training" framework ("PoST"), which intends to introduce a novel and practically-applicable approach to skill training periodization in the context of "specialist coaching"; and Part C, application of the "PoST" framework to training planning. This latter section (C) introduces practically applicable tools for sports coaches to use when periodizing and planning skill training with individual athletes or smaller groups of athletes (i.e., the current paper focuses on one to four athletes). Skill training, for this paper, is where the athlete is able to "seek, explore, discover, assemble, and stabilize the coordination of movement patterns" (Davids et al., 2008, p. 83), and training periodization is defined as systematic "short- and long-term planning to prescribe specific workloads and tasks" for athletes (also interchangeably termed as "learners," "performers," and "players" throughout this paper) (Farrow and Robertson, 2017, p. 1044).

Throughout the paper, the "specialist coaching" context of soccer goalkeeper (GK) training will be used as a vehicle to elaborate on the presented "PoST" framework. This particular context is chosen for various reasons; these include: (1) GK coaching is a very specialist coaching area, which sees GK coaches often working with player groups involving between one and four athletes; and (2) there appears to be continued prominence of traditional coaching approaches in GK training, which arguably limit representativeness (see Williams and Hodges, 2005). For example, in a recent study by Otte et al. (2019) using qualitative interviews, professional soccer GK coaches indicated each training session to typically follow a linear structure, where soccer-representative "complex activities" only account for around 30% of the total session time (as compared to 50–70% focusing on isolated technical work). This finding would further support the claim by Renshaw et al. (2010) that coaches need not only to individualize and systematically plan their skill training programmes for athletes, but also to maintain a learning environment that replicates dynamic performance situations.

PART A. SKILL TRAINING THEORY AND RESEARCH

In order to attempt to connect and apply academic knowledge to the "real coaching world," part one will briefly review the constraints-led approach (CLA) as a perspective on skill (acquisition) training; and part two introduces the role of the coach in managing the training environment by specifying three theory-driven challenges for practitioners.

CLA as a Theoretical Account on Skill Training

From a theoretical perspective, the CLA (underpinned and framed by dynamical systems, ecological psychology and non-linear pedagogy) will be adopted in order to review the acquisition of skills and its training periodization (see Renshaw and Chow, 2019; Renshaw et al., 2019b, for recent overviews of the CLA in skill acquisition training). In brief, the CLA, as an ecological model, advocates the underlying principle that open systems (e.g., athletes within invasion games or team ball games) are of non-linear nature and involve a mutual relationship with the performance environment (Pinder et al., 2011; Renshaw et al., 2016). During soccer games, for example, the GK's interception tasks (e.g., catching a shot on target) are dependent on numerous complex constraint interactions. These interpersonal interactions emerge from other players' movements and actions, as well as from further task (e.g., game score), environmental (e.g., changing weather or light conditions), and individual constraints (e.g., motor system fatigue, motivation, or emotions) (Davids, 2012, 2015; Correia et al., 2019; Renshaw et al., 2019b). This idea may lead to the notion that the game environment in open play situations at different points in time provides constantly changing constraints on the performer and thus, situations can never be identical (Renshaw and Chow, 2019). Consequently, GKs' self-organized and functional movement solutions will always have to be adapted slightly and contain internally-induced movement variability (see Kelso, 1995, for a theoretical overview); to provide an example: a GK catching a central shot on a rainy day (as compared to a sunny day) may demand different movement adaptations (e.g., arm and hand acceleration) in order to successfully achieve the aim of saving two comparable shots from similar distances.

Due to the ever-changing constraints on the performer, the CLA stresses two prevailing aspects (amongst others): (1) the athlete's ability to adapt and perform self-organized functional movement solutions in response to the emerging combination of task, environment, and individual constraints; and (2) the athletes' constant coupling of information and perception with movements and actions (Newell, 1986; Renshaw et al., 2010).

The former aspect can be underpinned by Bernstein (1967) "degrees of freedom problem," which demands performers to temporarily control relevant motor system degrees of freedom, so as to develop functional coordinative structures and "to ensure that movements are adapted to changing circumstances of performance" (Davids et al., 2008, p. 43). The latter aspect links to Gibson (1979; 2019) theory of affordances (i.e., opportunities for action and behavior, which act as information for motor executions and decision making in sport; Renshaw et al., 2010; Van Der Kamp et al., 2018). Emerging from "continuous interactions of an athlete with key features of a performance environment" (Davids, 2015, p. 53), these affordances are both body-scaled (i.e., depending on individual performer's action capabilities, such as technical abilities or fitness level) and action-scaled (i.e., depending on emergent environmental properties, such as teammates' movements; see Fajen et al., 2008, for a detailed review).

To relate the theoretical perspective of the CLA (in connection with its theoretical underpinnings) back to the subject of skill training and its periodization, it appears to be essential for coaches to gain an understanding of how they can organize and manipulate task constraints, so as to allow athletes to explore and discover relevant information within the training environment (Renshaw et al., 2016). Thus, the CLA provides a theoretical perspective, which can allow coaches to meet individual athlete's needs by manipulating the learning environment.

The Role of the Coach in Managing the Training Environment

The coaches' ability to provide athletes with appropriate affordances (primarily, via the use of task constraints) within game-representative training environments is incumbent for skill learning. In order to facilitate an appropriate training environment, there appear to be three key challenges for "specialist coaches" to manage and make decisions on; these include the key concepts of (1) the *representativeness of training*; (2) *stability and instability in training*; and (3) the *level of information complexity* (i.e., as managed by task constraint manipulations and the practice schedule of movement tasks). In detail, the former two challenges support training designs in terms of their *"replication value"* of actual performance demands and preparation for movement adaptability in dynamic team sports. The latter challenge helps practitioners to manage the *"level of appropriateness"* of the training environment, in relation to the performer's perceived task complexity and skill level.

Challenge 1: Introducing Representativeness and Task Specificity in Training

The merit of *representative learning designs* (i.e., measured by the degree to which skills acquired in practice transfer to the competitive environment; Renshaw and Chow, 2019) has been supported by an extensive body of research (see Pinder et al., 2011; Krause et al., 2018, 2019). In detail, representative training designs display three dominant notions: (1) providing learners with relevant affordances and perception-action couplings, so that they become perceptually attuned to critical information sources (e.g., Seifert et al., 2017; Orth et al., 2019); (2) facilitating training that holistically integrates motor processes (e.g., specific techniques) with perceptual-cognitive components (e.g., decision-making and tactical awareness; Ford et al., 2010; Broadbent et al., 2015; Farrow and Robertson, 2017); and (3) developing training designs that recreate action fidelity (i.e., the degree of correspondence between emerging behavior in a training task compared to competitive performance; Travassos et al., 2012) and functionality (i.e., the achievement of goals in the performance environment that are based on actions and constraints that athletes have been exposed to in the learning context; Pinder et al., 2011). Scientific evidence has found that athletes of dissimilar performance and development stages perceive different affordances. More advanced performers (across different sport contexts) appear to be perceptually better attuned and so tend to perceive more relevant information from the environment (e.g., Button et al., 2003; Travassos et al., 2012). Consequently, the idea of replicating dynamic competition demands in training, considering various levels of game-representativeness (see later), lies at the heart of the proposed "PoST" framework.

Challenge 2: Finding a Balance Between Stability and Instability

Movement adaptability explains the ability to produce and coordinate an appropriate ratio of stable and unstable movement behavior when required (see Renshaw et al., 2009; Seifert et al., 2013, for in-depth discussions of the dynamical systems theory applied to movement behavior in sports). While *movement stability* states the maintenance of a system's coordinative structure under perturbation, *instability* represents exploitation of fluctuations, so as to develop a functional response to perturbations caused by uncertainties in the dynamic environment (Conrad, 1983; Seifert et al., 2013). Along this continuum of maintaining the stability of actions (that provides a structure to performance and may enhance performer's motivation and confidence) and creating instability of actions (that leads to adaptive functional movement variability), "specialist coaches" have the opportunity to influence athlete's self-organization processes (Handford, 2006; Passos et al., 2008; Renshaw et al., 2009). Particularly, it is paramount that coaches systematically manipulate task constraints (e.g., goal or ball sizes) in training to intentionally create situations that lead to a change in an athlete's coordination (Renshaw and Chow, 2019). These directed and promoted changes, in particular, can be framed by the concept of "degeneracy," which describes achievement of the same output while (structurally) varying motor behavior (Renshaw et al., 2016); hereof, athletes learn to exploit various performance solutions and the stability of actions under dynamic and perturbing task constraints (Seifert et al., 2013). In simple terms, coach-induced coordination changes in training aim at enhancing an athlete's ability to achieve the same task goal in different ways and support "the search for, exploration of, and exploitation the use of the same solution to respond to different problems" (Correia et al., 2019, p. 124).

Challenge 3: Managing the Level of Information Complexity in Training

A process or task goal (e.g., the coordination of movement within a dynamic ball game) may be subjectively perceived as complex by an individual if "the amount of information required to control the process is large" (Backlund, 2002, p. 34). Adopting this description of complexity, its qualitative nature based on individually perceived dynamic system interactions must be highlighted (Davids, 2012). In particular, Yates (1978, 1987) states several attributes found in complex processes; these include: non-linearity, high numbers of degrees of freedom, and active interactions among parts and actors within the environment. All of these attributes underline the view that athletes are non-linear movement systems with inherent self-organization tendencies and mutual performance-environment interactions (Phillips et al., 2010; Davids, 2012, 2015; Seifert et al., 2013, 2017). Therefore, applying the concept of "information complexity" (interchangeable termed as "task complexity") to skill training in a "specialist coaching" setting appears to be appropriate. In particular, "specialist coaches" ought to manage informational complexity that challenges athletes' perception-action couplings while performing specific training tasks. By highlighting, dissimulating or expanding on perceptual-cognitive variables (e.g., the movement speed of a dribbling attacker), coaches may constrain the affordances available for individual athletes' exploration within the given training environment (Davids, 2015).

Notably, a particular challenge for coaches is stressed by the notion of similar training tasks being more or less feasible for different performers (i.e., according to their possibilities to successfully explore existing affordances). This idea aligns with Stoffregen (2003) definition of affordances as emergent properties of animal-environment systems and thus, states the subjectively perceived level of information complexity to create different challenges for each individual performer. In order to "provide an appropriate level of challenge" for individualized skill learning (Farrow et al., 2008, p. 497), coaches are therefore required to: (i) modify task constraints and equipment; and (ii) manage practice task schedules.

Task and equipment modification to manage information complexity

Alongside manipulating commonly advocated task constraints, such as instruction, rule changes, or playing area and surface adjustments (Correia et al., 2019), benefits of modifying equipment for the management of informational complexity are proposed. In particular, the removal or addition of perceptual information is considered to support or challenge athletes' exploration for functional perception-action couplings and movement solutions (Davids et al., 2008; Renshaw and Chow, 2019). These task constraint manipulations (i.e., to lower or increase perceived task complexity) may be beneficial for several reasons. Firstly, by modifying equipment, perceived task complexity may increase (e.g., differently weighted and shaped balls may cause less predictable flight and bounce patterns and increase task complexity for catching). Thus, modifications may support learners in organizing movement system degrees of freedom without disrupting subordinate levels of the central nervous system (Hodges and Franks, 2002; Davids et al., 2008). Specifically, added equipment may distract learners from consciously attending to and reinvesting in explicit details of movement mechanics (since a detailed elaboration of the "reinvestment theory" and the vast body of research in sport supporting the theory would go beyond this paper's scope, see Masters and Maxwell, 2008, for an overview). Consequently, implicit coordination of movement solutions and implicit learning processes, which have been shown to enhance robustness of skills under performance pressure, may be enhanced (Jackson and Farrow, 2005; Panchuk et al., 2014). Secondly, task manipulations based on equipment variation may guide athletes' visual search processes toward most critical information sources within the environment (e.g., an attacker wearing colored markers may guide GKs' gaze behavior toward critical postural and kinematic information sources, such as hip orientation and position; e.g., Ryu et al., 2013). Thirdly, added equipment may direct athletes toward alternative sensory and perceptual information (e.g., when impairing the visual array through specialized glasses, athletes' actions may need to be more strongly supported by acoustic arrays within the environment; Davids et al., 2008). Notably, despite proposed benefits of manipulating information complexity for the athlete(s) via equipment into skill training, "specialist coaches" need to be cautious about how and when to use training aids to support learning goals effectively.

The practice schedule of movement tasks to manage information complexity

The practice schedule describes the number of movement tasks and the order in which they are required to be performed by the athlete (Wulf and Shea, 2002). Due to this paper's primary focus on "specialist coaching" at the performance level (i.e., focused on skill refinement of complex skills executed by athletes in team sports), two distinct practice schedule arrangements are considered: "within-skill variability" (i.e., "discernible variation in the execution of the same skill"); and "between-skill variability" (i.e., "switching of skills during practice"; see Buszard et al., 2017, p. 2). While the former arrangement is likely to present an intra-task interference condition, the latter arrangement displays inter-task interference conditions. Notably an increase in information complexity may result from adjustments of both practice schedule arrangements.

From a CLA perspective, increasing both intra-task and inter-task interference (and thus, information complexity) may lead athletes to explore the training environment for more relevant information, thereby forming stronger perception-action couplings (Davids et al., 2008; Renshaw et al., 2019b). Research often advocates the benefits of increasing interference in order to encourage movement adaptations and enhance skill learning (Davids et al., 2008; Orth et al., 2019); particularly, this notion has been claimed to be advantageous for "skilled performers refining complex motor skills in applied environments" (Buszard et al., 2017, p. 11). While practice schedule manipulations may result in the demonstration of more unstable movement coordination in the short term, in the long-run, the induction of perturbations to performers’ perceptual-motor landscapes supposedly leads to more robust coordination structures (i.e., often termed as “attractors”); these structures can be applied to dynamic environmental changes by performers in team sports (Davids et al., 2008; Renshaw et al., 2010). Despite this perspective on advocating increased interference and variability in training, coaches may use practice schedules of movement tasks to regulate information complexity that performers are confronted with. The need for “specialist coaches” to consider the practice schedule is also strongly highlighted in the “SAP” framework (Farrow and Robertson, 2017) in terms of specificity of training and tedium challenges.

PART B. “PERIODIZATION OF SKILL TRAINING” FRAMEWORK

Part B, “Periodization of Skill Training” framework (“PoST”) (see **Figure 1**), presents and elaborates on the framework’s underlying structure, which is informed by above-mentioned theoretical insight, and has a particular focus on the second motor learning stage of “Skill Adaptability Training” (see below). Practical examples from soccer goalkeeping (i.e., a “specialist coaching” context, often constrained to a small number of players in the training environment) will be used to illustrate the training (sub-) stages.

Structure of the “PoST” Framework

Decades of research on motor skill learning have proposed numerous descriptive models of the process of skill acquisition. One common and ecological psychology-advocated model is Newell (1985) “model of motor learning,” which is the foundation of the “PoST” framework. Newell’s original model proposes three stages of motor learning (i.e., “skill coordination stage”; “skill control stage”; and “skill optimization stage”); these are based on Bernstein (1967) work on human movement systems (see Davids et al., 2008, for a detailed discussion of the model to dynamics of skill acquisition). Derived from the CLA perspective and in relation to Newell (1985) model, the “PoST” framework displays three main skill training stages (i.e. “Coordination Training,” “Skill Adaptability Training,” and “Performance Training”). For this paper, particularly the second stage (i.e., the “control stage” of coordinative structures, or termed as “Skill Adaptability Training”) will be highlighted in terms of skill training and learning.

Overall, when planning or periodizing skill training, “specialist coaches” are encouraged to focus on two main areas. Firstly, coaches ought to focus on a relevant skill training stage for the individual athlete (i.e., the x-axes of the graph). Secondly, coaches need to carefully manage the level of task representativeness (see challenge 1, and the right-hand y-axis) and perceived task complexity (see challenge 3, and left-hand y-axis). In relation to the demands of the actual performance environment and individual athlete’s capabilities and skill level, the framework provides a bi-dimensional representation of these factors. While the red dotted y-axis (i.e., on the right in **Figure 1**) displays a bi-directional measurement of game-representativeness, the black y-axis (i.e., on the left in **Figure 1**) presents the athletes’ perceived level of task complexity. In detail, game-representativeness is stated to progress and regress, in order to highlight the training design’s *“replication value”* of the actual performance environment (i.e., displayed by the horizontal, red solid line showing a maximum level of game-representativeness). Task complexity, in contrast to the primary y-axis, progressively increases in worth from “low” to “high” (i.e., the black curves on the graph); this progressive development aims to account for the subjective nature of individual’s perception of information complexity (e.g., while a training task remains at a moderate game-representativeness level, this task may be perceived as low in information complexity by GK A and high in complexity by GK B).

Notably, for coaches to further manage the level of perceived task complexity and facilitate a learning environment that is appropriate for the individual athletes, movement back and forth between the skill training stages (i.e., on the x-axis) should be considered. In particular, practitioners may need to facilitate “skill reorganization processes” (i.e., (re)freezing motor system degrees of freedom to induce movement stability) and “skill optimization processes” (i.e., the functional grouping of an increased amount of motor system degrees of freedom) (Bernstein, 1967; Davids et al., 2008). The horizontal movements between various skill training (sub-)stages for single learners are supported by basic tenets of non-linear pedagogy; these, in particular, highlight: (1) motor learning as a non-linear process (i.e., athletes show different rates of skill learning and different time scales for progression; e.g., Phillips et al., 2010; Renshaw and Chow, 2019); (2) the need for individualized and varied pathways for learning (e.g., Chow, 2013); and (3) the absence of a single best way of learning and teaching (i.e., the same training approach may affect individual performer’s learning differently; e.g., Correia et al., 2019).

“Coordination Training”

The first (left) part of the skill training framework (i.e., “Coordination Training”) is focused on searching for and exploring coordination movements within the emerging training environment. In order to acquire basic movement patterns and stable coordination structures, performers in this stage should experience rather low levels of environmental variability and task complexity (i.e., the gray line in this sub-stage remains at a moderate or lower level of game-representativeness; Renshaw and Chow, 2019). Particularly, the method of task simplification may be useful for coaches in this skill training stage. This approach of using “scaled-down versions of tasks [that] are created in practice and performed by learners” (Chow et al., 2007, p. 270) aims at maintaining relevant information-movement couplings and constraint interactions, while blocking degrees of freedom in order to meet the athlete’s skill level (Davids et al., 2008; Correia et al., 2019).

With regards to the soccer GK context, this phase would predominantly focus on the acquisition of fundamental movements (e.g., catching and diving), while retaining intact player-environment interactions; for example, a coach may

FIGURE 1 | The "Periodization of Skill Training" framework ("PoST" framework).

dribble and shoot slowly on a GK—this would allow the GK to get set, perceive the moment of ball-foot contact (for the shot) and time movement coordination toward catching the shot. Coaches would allow learners to repeatedly freeze motor system degrees of freedom under constant environmental conditions in order to manage the task demands and achieve task outcomes (Seifert et al., 2013; Buszard et al., 2017). Immediately upon developing (some) movement stability, coaches are encouraged to change the training structure and organization (Wulf and Shea, 2002; Farrow and Robertson, 2017). In other words, movement consistency under controlled environmental conditions over a set period of time (e.g., several training sessions) would be regarded as a trigger for coaches and athletes to (more permanently) progress to the second skill training stage of "Skill Adaptability Training."

"Skill Adaptability Training"

With the aim of enhancing the adaptability, functionality, and robustness of motor skills under perturbation of dynamic environments, the second development phase, "Skill Adaptability Training," focuses on skill learning. Here, performers are challenged to self-organize and adapt coordinative structures with complex and representative constraints of the dynamic performance environment (Davids et al., 2006; Araújo and Davids, 2011; Renshaw and Chow, 2019). The idea that coordinative structures become more open to constantly changing information sources and environmental perturbations drives this non-linear training stage (Davids et al., 2008).

In order for coaches to encourage movement variability and enhance skill learning, the "PoST" framework proposes three sub-stages (see **Figure 1**); these stages are termed as: (1) "Movement Variability Training" (i.e., the first green section from the left in the framework); (2) "Complex Training" (i.e., the second green section from the left); and (3) "Team-based Training" (i.e., the third green section from the left).

"Movement variability training" stage

The first sub-stage of "Skill Adaptability Training" focuses on individualized training contexts consisting primarily of one (or two) athletes and a "specialist coach" (i.e., notably, the training environment is constrained in terms of game-representativeness, due to the low number of participants). Performers, here, focus on movement variability, which aims to enhance the ability to adapt movement parameters in response to changing constraints in the environment. This sub-stage is driven by the aim of challenging performers to more actively search for relevant information sources and adapt micro-component features of movement solutions (i.e., "within-skill variability"). Predominantly, this would be within a stable affordance landscape and under varying levels of task complexity. In other words, while the practice schedule of movements is largely known to the performer, motor executions need to be flexibly adapted under changing constraints.

Methodical approaches within this stage of "Movement Variability Training" could include, for example, the differential learning approach or the addition of changing parameters and modified equipment to the movement task at hand. The former approach demands learners to perform each movement repetition with slight "fluctuations" (i.e., variations). These fluctuations lead individual performers to search for a movement optimum from the entire range of possible intra-movement variations (e.g., Schöllhorn et al., 2009; Farrow and Robertson, 2017). The latter methodical approach of inducing perceptual-cognitive interference, on top of confronting learners with movement tasks, aims to increase/decrease task complexity and challenge exploration of critical informational sources emerging from performer-environment interactions. In particular, these exploratory processes may be initiated in different ways; for instance, by adding task constraints (e.g., by increasing time or opponent pressure and changing object parameters). Furthermore, modifying equipment in order to support or limit sensory perception could add benefits (see challenge 3). For example, **Figure 2** (below) displays a soccer GK training session with an individual GK that focuses on the single movement task of "diving sideways." While the GK is confronted with this movement task, the coach could manipulate invariant and variant information variables, such as object parameters and the trajectory (e.g., by adjusting the ball speed, ball size, or shooting distance) and add further informational complexity through inducing perceptual-cognitive interference (e.g., special glasses limiting peripheral vision). In turn, this would challenge the GK to vary spatiotemporal kinematic movement parameters, such as arm acceleration and timing toward the ball, while also having to deal with supplemental visual limitation.

Overall, this first skill learning sub-stage focuses on single movement tasks under perceptual-cognitive interference, and thus, the level of task complexity may either fall short of or exceed the demands of competition (i.e., the sub-stage displays two black curves below and above the red solid line, respectively). Despite acknowledging that aforementioned perceptual-cognitive interference may make the training environment less game-representative in terms of superficial similarities (i.e., the black lines do not intersect the red solid line), we propose that these modifications may have beneficial effects for skill refinement (see challenge 3).

"Complex training" stage

Transitioning from the first sub-stage (focusing on single movement tasks in training environments including one or two athletes), the "Complex Training" stage aims at confronting performers with multiple movements via further increase of information complexity (e.g., small training groups consisting of up to four athletes in soccer goalkeeping). At first, these movement tasks may share common features and structural task similarities (Braun et al., 2009; Braun, 2013); examples, hereof, could contain shared movement sequences and interception tasks (e.g., the GK's arm and hand movement and acceleration toward catching a high cross or a central shot above the athlete's head) or shared perceptual tracking requirements used to develop functional perception-action couplings (Hebert et al., 1996). By limiting movement tasks to those with structural commonalities, athletes could be encouraged to explore a smaller perceptual-motor landscape, while continuously trying to adapt movement solutions and achieve the task outcome. Considering these rather stable training conditions, task complexity, at first, may be perceived as low to moderate by athletes (i.e., the low part of the black curve in the second green sub-stage from the left). The level of game-representativeness may not quite reach the red solid line (i.e., maximum game-representativeness).

Moving up to the black curve in this "Complex Training" sub-stage, practice task schedules may highlight "between-skill variability" of unrelated movement skills. Driven by the modification of various task constraints, athletes' perceived task complexity may increase significantly. For example, training tasks in which the coach or further attackers could shoot on goal from various angles and distances would require the GK to perceive relevant kinematic information from various sources (e.g., multiple possible shooters). Additionally, GKs here would be challenged to explore an increased number and complexity of affordances within the dynamic training environment and thus, have to effectively couple information with movements (see **Figures 3**, **4** for examples). Due to constraint manipulations, such as increased intensity and loading (e.g., leading to fatigue), stress (e.g., opponent pressure), and the number of repetitions experienced (within a relatively short time), the later phase of this sub-stage may work above the red solid line (i.e., the upper part of the black curve in the second green sub-stage). While containing representative elements (e.g., the perception of kinematic information from a shooting attacker), an exact replication of game demands may only be achieved to a certain extent (e.g., in the attacking situation, the GK may only be required to intercept shots or crosses from a predictable range of distances and angles; **Figure 4**). Despite the limited number of game-representative affordances, these training forms are likely to be perceived as highly complex by athletes.

"Team-based training" stage

Under the umbrella term of "Team-based Training," this third sub-stage aims to closely replicate game-representative performer-environment interactions according to principles from CLA and non-linear pedagogy (Renshaw and Chow, 2019). In contrast to the above-mentioned context of "specialist" individual or small group coaching, this training stage refers to training with an entire team or larger groups of athletes (e.g., four or more athletes in soccer training). Consequently, with an increased number of athletes involved in training, facilitating game-representative affordances arguably becomes significantly more accessible for coaches. In particular, by re-introducing aforementioned "playing forms" (e.g., small-sided games; see introduction), athletes are likely to be confronted with complexity of information that matches the complexity perceived in games (i.e., working closely around the red solid line); thus, coaches may attune athletes to relevant action opportunities. In order to further elaborate on this idea, we adopt previously-established categorizations of "playing forms" in team sports; these, for the purpose of this paper, include (1) "phase-of-play situations"; and (2) "conditioned games," "small-sided games," and "larger games" (see Partington et al., 2014; O'Connor et al., 2017, for detailed discussions).

Firstly, "phase-of-play situations" describe "uni-directional match-play toward one goal [or target]" (Ford et al., 2010, p. 487). Training of game-representative situations, in particular, may include repeated simulations of attackers penetrating an opponent's defense in order to create goal scoring opportunities

FIGURE 2 | "Movement Variability Training" example: the GK is asked to repeatedly dive sideways and deal with low shots. While the coach(es) constantly manipulate(s) object parameters and the trajectory by using different sized balls and various shooting and throwing techniques, further perceptual-cognitive interference may be added by wearing special glasses to limit the GK's vision. Notably, the line in the middle of the goal (as a task constraint) aims at supporting the GK by providing additional spatial orientation.

FIGURE 3 | "Complex Training" example: a GK-specific shot-stopping exercise that requires three GKs to defend the three goals. Further GKs act as attackers in the center of the field, in order to increase task complexity and representativeness.

FIGURE 4 | "Complex Training" example: complex training exercise in a GK-specific training session with four GKs. A break-through situation inside the box results in a "cut-back pass" into the middle or a direct shot on goal. The GK is required to perceive relevant information variables (e.g., the attacker on the ball) and exploit the given affordances, so as to achieve the task of defending the goal.

(O'Connor et al., 2017). Thus, constraints that are frequently found within performance environments are repeatedly explored; for example, **Figure 5** presents a 3v2 attacking situation at the edge of the goal box in soccer that confronts the GK with emerging attacker-defender interactions.

Secondly, a three-fold differentiation for training games is proposed; these include: (1) "conditioned games"; (2) "small-sided games"; and (3) "larger games" (i.e., games "during training where players work in teams of 5 or more"; O'Connor et al., 2017, p. 650). These playing forms aim to facilitate an environment in which performers or teams compete against each other in (free) play, so as to develop task-specific and adaptable coordination patterns (Broderick and Newell, 1999; Rink, 2001; Davids et al., 2008, 2013). While "conditioned" and "small-sided games" strongly promote exploration of interpersonal interactions, they often constrain players in regard to space, time and player numbers included (Davids et al., 2013; O'Connor et al., 2017). Consequently, the additional use of "larger games" for replication of game actions appears to be another cornerstone of this skill training sub-stage. **Figure 6**, for example, displays a "larger game" consisting of an 11-vs.-11 soccer training game played on a marginally shortened soccer pitch. This training organization, although harder to destabilize (as compared to small-sided games; Davids et al., 2013), arguably displays one of the highest levels of representativeness (in regard to the demands that the GK will face in competitive soccer games).

In sum, while training games themselves drive learning, it is the coaches that further facilitate the training environment by manipulating task constraints (e.g., field size, rules, equipment) and by driving feedback processes through instructional strategies of questioning and guided discovery (Chow, 2013; Renshaw et al., 2016). As indicated by the wavy black line (i.e., the dark-green sub-stage second from the right in the framework), it is this particular sub-stage of "Team-based Training" that works to closely replicate actual game demands (i.e., the wavy black line intersects the red solid line). Thus, this skill training sub-stage presents one (if not, the most) critical component of athlete development. Considering the importance of this sub-stage, we would even propose that any sports coach, working with larger groups of athletes and aiming at skill learning, adheres to "Team-based Training" approaches and constantly introduces playing forms to training. In individualized "specialist coaching" constrained to small groups of athletes (which forms a focus of this paper), however, the skill training "sub-stages" of "Movement Variability Training" and "Complex Training" provide valuable alternatives. The authors would also like to acknowledge the challenge of a "specialist coach" working in isolation from team trainings and thus, encourage strong communication with the head coach or head of programme to ensure that long-term development of individual athletes is considered from an holistic and athlete-centered point of view. In any professional club or team set-up, there is a need for multi-disciplinary overview of development for each performer, so as to monitor progressions and avoid overtraining, injury or under-training; this overview is often the role of the head coach.

"Performance Training"

The third developmental stage of the "PoST" framework (**Figure 1**, the crimson-colored training section on the right in the framework) indicates a shift away from Newell's initial third stage of "skill optimization," which originally aims to enhance the energy efficiency and adaptability of movements in perturbing and complex environments (Newell, 1996). According to the "PoST" framework, athletes in the "performance training" stage find themselves close to competition. Consequently, skill development may not necessarily be the primary focus (Farrow and Robertson, 2017), but rather exploiting the performance environment for maximum return or efficiency.

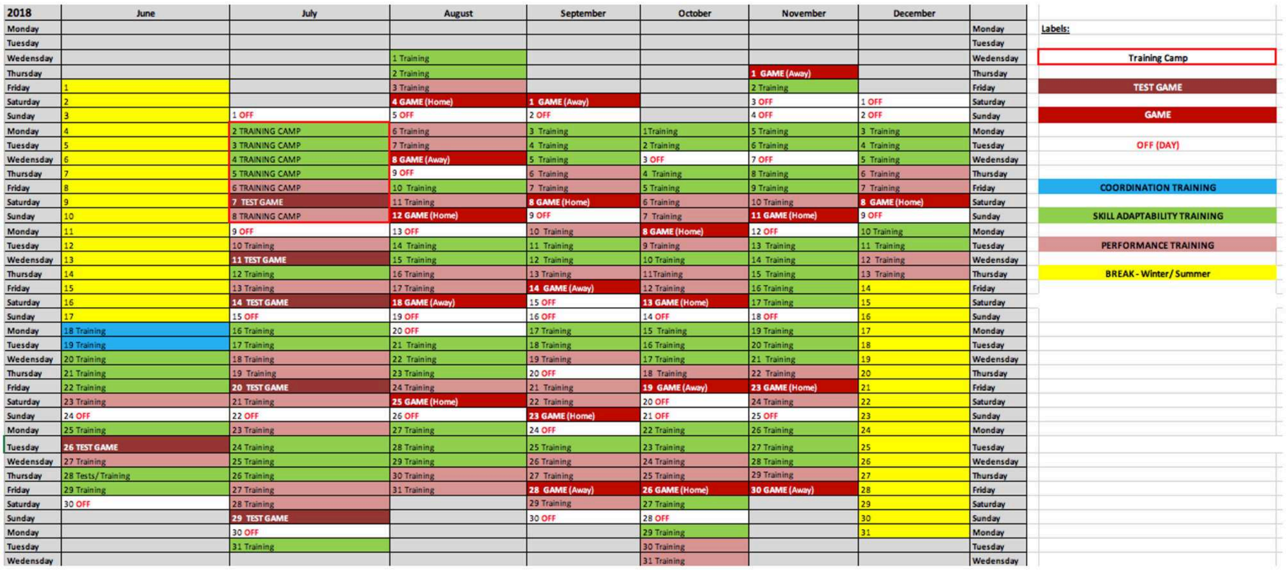
FIGURE 5 | "Team-based Training" example: a "phase-of-play situation" presenting a 3v2 on one goal. The GK is required to respond to the emerging interactions between the attacking and defending team in order to coordinate functional movement solutions.

FIGURE 6 | "Team-based Training" example: a 'larger game' presenting an 11-vs.-11 soccer training game played on a shortened soccer pitch. In addition to the task manipulation of the field size, further line markings across the field aim to constrain the playing surface and support players' tactical positioning during the game.

Particularly, on the one hand, "performance training" leading up to competition in team ball sports may initially contain training designs high in game-representativeness (i.e., perceived task complexity works closely around the red line in the days/weeks prior to competition). Under the overarching focus of optimizing team performances, soccer coaches, for example, would highlight performance-driven preparation in a team-tactical 11-vs.-11 training game. By explicitly instructing the "B-team" to replicate behavior of the upcoming opponent (e.g., formation or style-of-play), the training environment and individual exploration of movement opportunities is constrained by the coach; this is despite the training game itself being highly representative in terms of perceptual-cognitive and skill demands. On the other hand, closely preceding competition, factors such as performance stability and preparation through implementing athlete-led training routines (e.g., a pre-game warm-up routine led by the soccer GK) may be deemed (significantly) more important to athletes than learning and skill development. Therefore, it is proposed that the (specialist) coach in the "performance training" phase directly prior to competition re-highlights the importance of movement stability in order to build up confidence (i.e., perceived task complexity and game-representativeness stay well below the red solid line).

PART C. APPLICATION OF THE "POST" FRAMEWORK TO TRAINING PLANNING

The former parts (A and B) have focused on the introduction of the "PoST" framework's theoretical foundation, underlying structure and the challenges that coaches need to consider when managing the training environment. In a final step, it is salient to demonstrate the framework's distinctive applied value for "specialist coaches" when used for practical training periodization and planning. Therefore, this section is particularly focused on: (1) the course of (multiple) training months and



2018	June	July	August	September	October	November	December	
Monday								Monday
Tuesday								Tuesday
Wedensday			1 Training					Wedensday
Thursday			2 Training			1 GAME (Away)		Thursday
Friday	1		3 Training			2 Training		Friday
Saturday	2		4 GAME (Home)	1 GAME (Away)		3 OFF	1 OFF	Saturday
Sunday	3	1 OFF	5 OFF	2 OFF		4 OFF	2 OFF	Sunday
Monday	4	2 TRAINING CAMP	6 Training	3 Training	1Training	5 Training	3 Training	Monday
Tuesday	5	3 TRAINING CAMP	7 Training	4 Training	2 Training	6 Training	4 Training	Tuesday
Wedensday	6	4 TRAINING CAMP	8 GAME (Away)	5 Training	3 OFF	7 OFF	5 Training	Wedensday
Thursday	7	5 TRAINING CAMP	9 OFF	6 Training	4 Training	8 Training	6 Training	Thursday
Friday	8	6 TRAINING CAMP	10 Training	7 Training	5 Training	9 Training	7 Training	Friday
Saturday	9	7 TEST GAME	11 Training	8 GAME (Home)	6 Training	10 Training	8 GAME (Home)	Saturday
Sunday	10	8 TRAINING CAMP	12 GAME (Home)	9 OFF	7 Training	11 GAME (Home)	9 OFF	Sunday
Monday	11	9 OFF	13 OFF	10 Training	8 GAME (Home)	12 OFF	10 Training	Monday
Tuesday	12	10 Training	14 Training	11 Training	9 Training	13 Training	11 Training	Tuesday
Wedensday	13	11 TEST GAME	15 Training	12 Training	10 Training	14 Training	12 Training	Wedensday
Thursday	14	12 Training	16 Training	13 Training	11Training	15 Training	13 Training	Thursday
Friday	15	13 Training	17 Training	14 GAME (Away)	12 Training	16 Training	14	Friday
Saturday	16	14 TEST GAME	18 GAME (Away)	15 OFF	13 GAME (Home)	17 Training	15	Saturday
Sunday	17	15 OFF	19 OFF	16 OFF	14 OFF	18 OFF	16	Sunday
Monday	18 Training	16 Training	20 OFF	17 Training	15 Training	19 Training	17	Monday
Tuesday	19 Training	17 Training	21 Training	18 Training	16 Training	20 Training	18	Tuesday
Wedensday	20 Training	18 Training	22 Training	19 Training	17 Training	21 Training	19	Wedensday
Thursday	21 Training	19 Training	23 Training	20 OFF	18 Training	22 Training	20	Thursday
Friday	22 Training	20 TEST GAME	24 Training	21 Training	19 GAME (Away)	23 GAME (Home)	21	Friday
Saturday	23 Training	21 Training	25 GAME (Home)	22 Training	20 OFF	24 Training	22	Saturday
Sunday	24 OFF	22 OFF	26 OFF	23 GAME (Home)	21 OFF	25 OFF	23	Sunday
Monday	25 Training	23 Training	27 Training	24 OFF	22 Training	26 Training	24	Monday
Tuesday	26 TEST GAME	24 Training	28 Training	25 Training	23 Training	27 Training	25	Tuesday
Wedensday	27 Training	25 Training	29 Training	26 Training	24 Training	28 Training	26	Wedensday
Thursday	28 Tests/ Training	26 Training	30 Training	27 Training	25 Training	29 Training	27	Thursday
Friday	29 Training	27 Training	31 Training	28 GAME (Away)	26 GAME (Home)	30 GAME (Away)	28	Friday
Saturday	30 OFF	28 Training		29 Training	27 Training		29	Saturday
Sunday		29 TEST GAME		30 OFF	28 OFF		30	Sunday
Monday		30 OFF			29 Training		31	Monday
Tuesday		31 Training			30 Training			Tuesday
Wedensday					31 Training			Wedensday

Labels:

Training Camp

TEST GAME

GAME

OFF (DAY)

COORDINATION TRAINING

SKILL ADAPTABILITY TRAINING

PERFORMANCE TRAINING

BREAK - Winter/ Summer

FIGURE 7 | An example of a GK skill training periodization macro-cycle over the course of seven months during a professional soccer season.

weeks (i.e., here described as macro- and micro-cycles); and (2) the structure of single training sessions (i.e., including single units within a training session). Notably, the following sub-sections will continue to use the soccer GK context; however, the authors encourage "specialist coaches" from other team ball sports to adjust and utilize the same conceptual structure for skill training periodization and planning.

Application to Training Planning Over Macro- and Micro-Cycles

On the macro- and micro-levels for training planning, coaches may be confronted with the various aforementioned challenges; for example, taking into account the game-representativeness of the training task, the level of perceived task complexity and the athlete's skill development stage. In addition, further external variables, like the number of athletes involved in the training session, the competition schedule, and training focus (i.e., from technical-tactical, physical and psychological perspectives) constrain how skill training over multiple months, week, and sessions could be methodically structured. In order to provide practical examples, skill training periodization (based on the "PoST" framework) over the course of multiple months and weeks within a year-long season are presented. **Figures 7**, **8**, here, display the training schedule of advanced under-20s youth GKs.

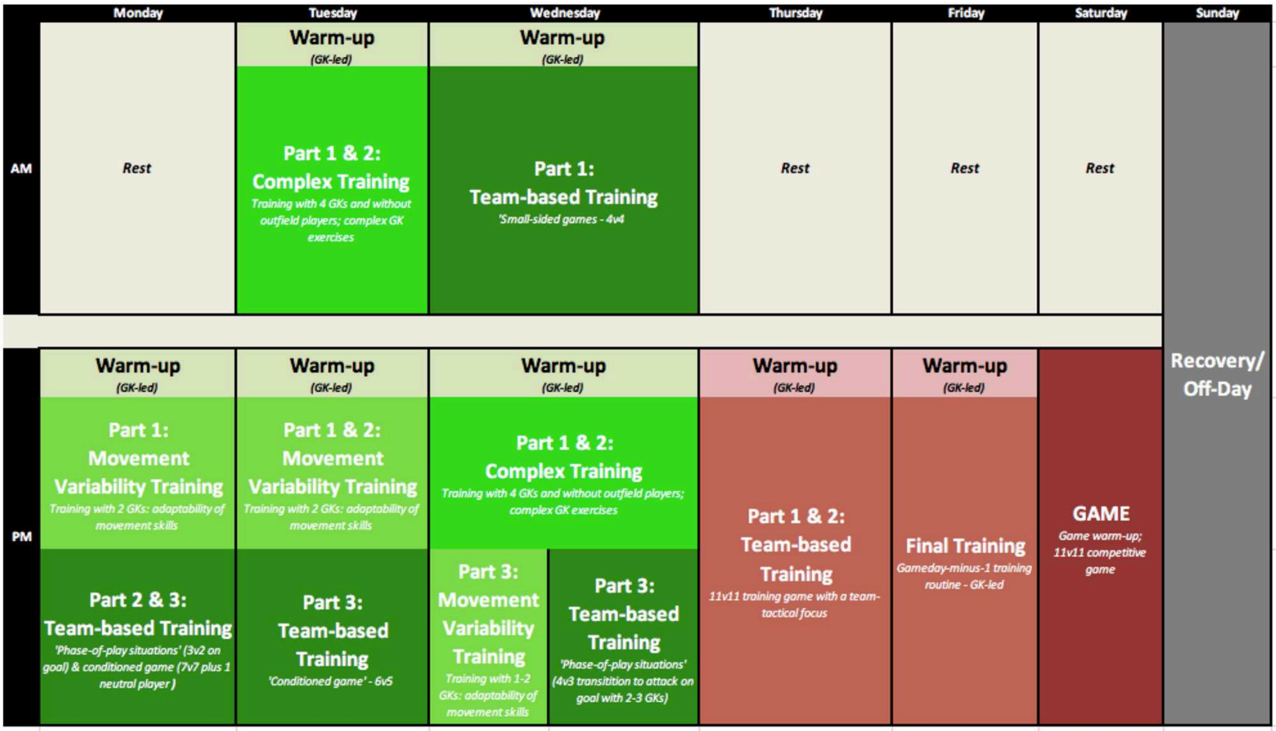
Firstly, the training periodization schedule in **Figure 7** presents an example of training session planning over the course of seven months during a professional soccer season (i.e., a macro-cycle). In consideration of the proposed skill training stages (i.e., "Coordination Training," "Skill Adaptability Training," and "Performance Training"), the schedule includes various training and game activities, such as test games, competitive games, training camps, and regular training sessions. By systematically planning skill training months in advance, "specialist coaches" have the opportunity to gain an early insight into critical training weeks for skill learning (e.g., in contrast to training weeks with a focus on performance exploitation).

Secondly, **Figure 8** exhibits an exemplary training week including various skill training sub-stages (i.e., a micro-cycle). In detail, the plan includes seven training sessions and a competitive game. The training sessions are periodized and planned based on the "PoST" framework's training stages of "Skill Adaptability Training" and "Performance Training"; for example, learning-focused "Movement Variability Training," "Complex Training," and "Team-based Training" during the first days of the week (i.e., indicated by the green-shaded boxes in **Figure 8**) is accompanied by training days focusing on "Performance Training" in preparation for competitive games (i.e., indicated by the maroon-shaded boxes). Particularly, this weekly pre-planned training schedule proves beneficial for "specialist coaches" when designing single training sessions in detail (see below).

Finally, we acknowledge that while the majority of "specialist coaches" may not have the luxury of periodizing skill training longitudinally, the framework itself has the scope to assist practitioners in this matter. Additionally, the "SAP" framework (see Farrow and Robertson, 2017) provides valid measures to monitor skill development.

Application to Training Planning for Single Training Sessions

For training planning, the "PoST" framework offers an effective tool to guide coaches in the design of the structure of training sessions (including its various units). Prior to designing training exercises, the coach has the opportunity to pre-plan and individualize the methodical training approach. By selecting (1) relevant skill training (sub-) stages; (2) task constraints



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	*Rest*	**Warm-up** *(GK-led)* **Part 1 & 2: Complex Training** *Training with 4 GKs and without outfield players; complex GK exercises*	**Warm-up** *(GK-led)* **Part 1: Team-based Training** *'Small-sided games - 4v4*	*Rest*	*Rest*	*Rest*	**Recovery/ Off-Day**
PM	**Warm-up** *(GK-led)* **Part 1: Movement Variability Training** *Training with 2 GKs: adaptability of movement skills* **Part 2 & 3: Team-based Training** *'Phase-of-play situations' (3v2 on goal) & conditioned game (7v7 plus 1 neutral player)*	**Warm-up** *(GK-led)* **Part 1 & 2: Movement Variability Training** *Training with 2 GKs: adaptability of movement skills* **Part 3: Team-based Training** *'Conditioned game' - 6v5*	**Warm-up** *(GK-led)* **Part 1 & 2: Complex Training** *Training with 4 GKs and without outfield players; complex GK exercises* **Part 3: Movement Variability Training** *Training with 1-2 GKs: adaptability of movement skills* **Part 3: Team-based Training** *'Phase-of-play situations' (4v3 transitition to attack on goal with 2-3 GKs)*	**Warm-up** *(GK-led)* **Part 1 & 2: Team-based Training** *11v11 training game with a team-tactical focus*	**Warm-up** *(GK-led)* **Final Training** *Gameday-minus-1 training routine - GK-led*	**GAME** *Game warm-up; 11v11 competitive game*	

FIGURE 8 | An example of the skill training (periodization) schedule of advanced (professional) U-20s youth GKs throughout a training week. Notably, the choice of training "sub-stages" and training content is constrained (1) by the number of GKs participating in the training session, and (2) by fitting the session around team-based training parts.

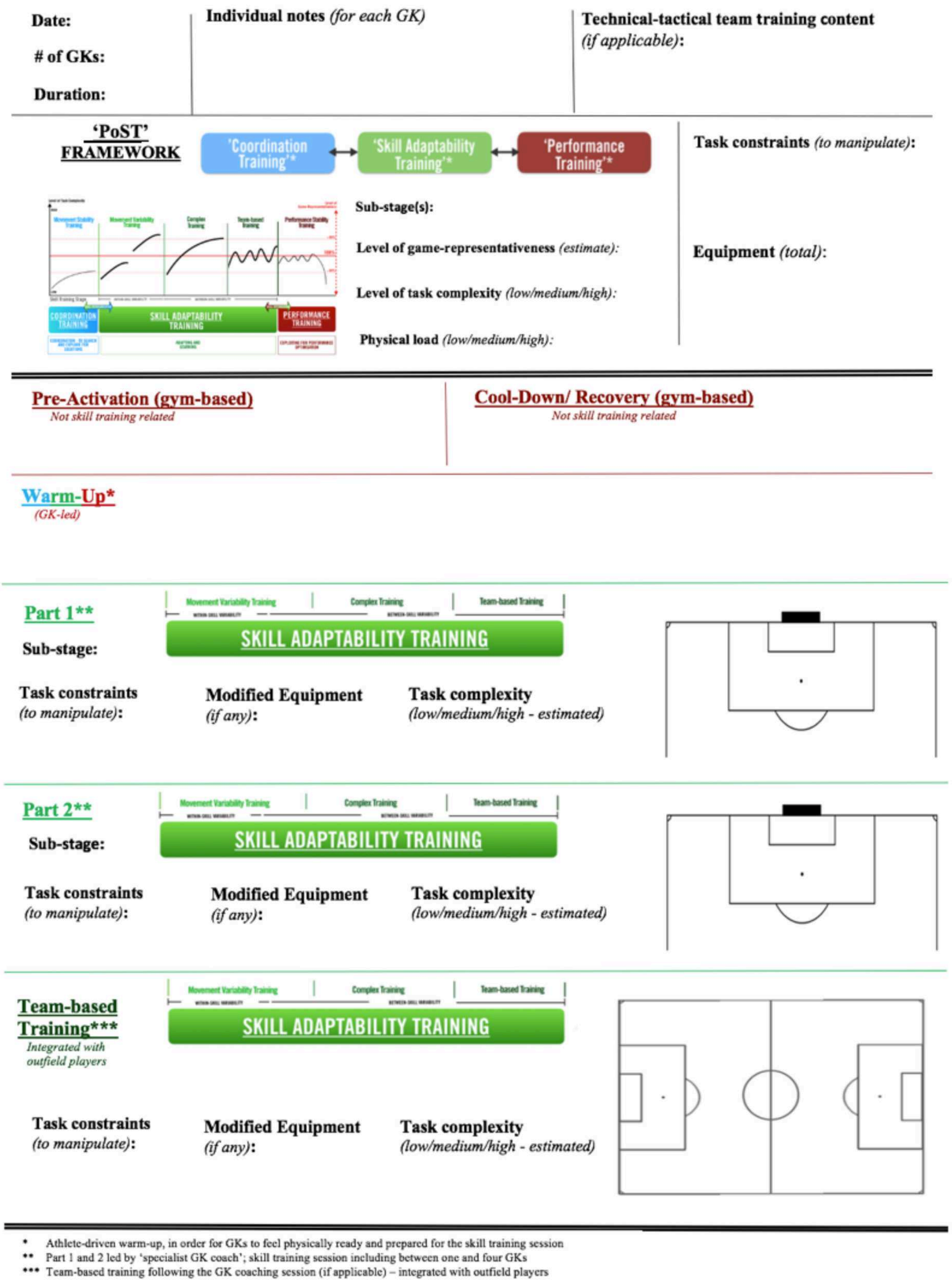
(that may be manipulated); (3) modifications of equipment (if applicable); and (4) estimating perceived task complexity and physiological load that is placed upon athletes, the coach can gain in-depth insight into the goals of the training session; this is before spending any time designing practical training exercises and games. For example, prior to a soccer GK training session, the "PoST" framework may provide a tool for designing and planning units within this single training session. **Figure 9**, hereof, displays a training session template specifically tailored toward the soccer GK training context.

Using the aforementioned example of advanced U-20s youth GKs, the structure of a Wednesday afternoon training session with four GKs could primarily focus on skill learning (see **Figure 8**). In detail, the session could commence with a brief and GK-led "warm-up" in order to physically and mentally prepare the GK for the session. Next, the session would quickly proceed toward "Complex Training." Here, in particular, the coach could design a training environment that focuses on "between-skill variability." Mainly limited by a small training group size of four GKs, training session parts 1 and 2 would aim to manipulate task constraints and equipment in order to develop the GK's ability to explore a complexity of affordances within the dynamic training environment. While training exercises at first are likely to be rather low in game-representativeness, they may be high in task complexity (i.e., due to modification of equipment and task constraints). Finally, toward the last part of this training session, the GK training group would be split depending on the coach's observations in parts 1 and 2 (e.g., a GK that was overly challenged by task complexity would be separated from less challenged GKs in part 3). For example, one GK would move into "Movement Variability Training" to focus on "within-skill variability," rather low in task complexity (i.e., adapting movement parameters in response to changing constraints). Simultaneously, the other GKs would join the outfield players for "phase-of-play situations," which would be rather high in task complexity (e.g., more game-representative 4v3 transitions to attack on goal).

Overall, "specialist coaching" commonly displays constraints such as working with limited athlete numbers or having to fit training session parts around team-based training (see example above). Thus, it remains an important challenge for these "specialist coaches" to enforce non-linearity throughout single session designs (e.g., similar to training designs applied by alternative approaches, such as GBAs).

CONCLUDING REMARKS

In summary, this paper pursues the goal of practically applying skill training theory by proposing a skill training periodization framework. The "PoST" framework has the potential to provide guidance for "specialist sport coaches" (not only in soccer goalkeeping) on designing appropriate training environments



Date:

# of GKs:

Duration:

Individual notes *(for each GK)*

Technical-tactical team training content *(if applicable)*:

'PoST' FRAMEWORK

'Coordination Training'* ↔ 'Skill Adaptability Training'* ↔ 'Performance Training'*

Sub-stage(s):

Level of game-representativeness *(estimate)*:

Level of task complexity *(low/medium/high)*:

Physical load *(low/medium/high)*:

Task constraints *(to manipulate)*:

Equipment *(total)*:

Pre-Activation (gym-based)
Not skill training related

Cool-Down/ Recovery (gym-based)
Not skill training related

Warm-Up*
(GK-led)

Part 1**

Sub-stage:

Task constraints *(to manipulate)*:

Modified Equipment *(if any)*:

Task complexity *(low/medium/high - estimated)*

Part 2**

Sub-stage:

Task constraints *(to manipulate)*:

Modified Equipment *(if any)*:

Task complexity *(low/medium/high - estimated)*

Team-based Training***
Integrated with outfield players

Task constraints *(to manipulate)*:

Modified Equipment *(if any)*:

Task complexity *(low/medium/high - estimated)*

- * Athlete-driven warm-up, in order for GKs to feel physically ready and prepared for the skill training session
- ** Part 1 and 2 led by 'specialist GK coach'; skill training session including between one and four GKs
- *** Team-based training following the GK coaching session (if applicable) – integrated with outfield players

FIGURE 9 | Example single training session template using the "PoST" framework to plan single units within a soccer GK training session. For this session plan, particularly, the stage of "Skill Adaptability Training" is the focus. Throughout part 1, part 2, and a "Team-based Training" part (if applicable), the coach can design a session based on: (1) task constraint manipulations; (2) equipment modification; and (3) estimated perceived task complexity for GKs involved in the session.

that consider the representative demands of competition. In particular, three aspects appear to underline the framework's merit: (1) the applicability to training planning both on the macro- and micro-level (i.e., over the course of multiple training months and weeks); (2) the applicability to single training session and unit planning; and (3) the support for practitioners to adequately manipulate the training environment toward individual athletes' needs; i.e., by introducing training challenges under consideration of representative game demands and the athlete's perceived level of task complexity.

Despite the proposed framework providing valuable practical support for sport coaches, its theoretical limitations need to be addressed. These limitations aim to encourage future multi-disciplinary research based on the proposed skill training stages. Firstly, the paper does not provide quantitative approaches toward assessing game-representativeness of training; however, the "SAP" framework by Farrow and Robertson (2017) does an excellent job of this. By focusing on comprehensively transferring academic skill training theory to practical coaching, the "PoST" framework proposes estimates of game-representativeness for certain skill training stages. The validation of "practice assessment tools," such as a recently introduced tennis-specific assessment tool would add further merit (see Krause et al., 2018). Additionally, the measurement of action fidelity and functionality may prove valuable in assessing game-representativeness of training (Farrow and Robertson, 2017; Krause et al., 2019). Particularly, the use of technological tools applied in performance analysis (e.g., wearable technologies or video analysis software) may assist researchers and coaches in comparing training designs with performance environments; for example, Travassos et al. (2012) measured action fidelity and training task representativeness by comparing ball speed and passing accuracy in various futsal training conditions with data from competitive games. Secondly, due to its qualitative nature, the concept of information complexity makes it difficult for coaches to evaluate what athletes may perceive as (too) complex. Consequently, the "PoST" framework proposes the use of a subjective concept for individualizing skill training; this approach needs further exploration and empirical research in order to scale and objectively measure informational complexity as perceived by athletes during skill training. For example, researchers could apply and refine internal measurement protocols for monitoring athletes' perceived informational complexity, such as the recently introduced "rating of perceived challenge" (RPC; see Hendricks et al., 2019). These internal evaluations could be further combined with external measures, such as the actual output produced by an athlete (e.g., the passing accuracy of a soccer player; e.g., Chow et al., 2008). On this subject, a more complex training task "is assumed as a proxy for increased error" (Farrow and Robertson, 2017, p. 1047).

As a final remark, understanding that there is "no silver bullet for all teaching (coaching) and learning" represents the responsibility for coaches to individualize and periodize skill training based on athletes' needs (Renshaw et al., 2010, p. 135). Considering the emerging context of "specialist coaches" working solely with individual athletes or small groups of athletes, there appears to be a fruitful opportunity for individualized control of information complexity that athletes are confronted with. If a coach working individually with one or two athletes cannot manipulate task constraints in order to cater to each individual athlete's needs, then one might argue that this role would be even harder for a head coach working with a squad of 20–30 athletes at the same time.

ETHICS STATEMENT

Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

FO developed the conception of the model. S-KM and SK contributed to re-design and presentation of the model. FO wrote the first draft of the manuscript. S-KM and SK wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Exploratory Analysis of Treading Water Coordination and the Influence of Task and Environmental Constraints

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The radical embodied cognition approach to behavior requires emphasis upon how humans adapt their motor skills in response to changes in constraint. The aim of this exploratory study was to identify how the typical coordination patterns used to tread water were influenced by constraints representative of open water environments. Twenty-three participants were measured while treading water (TW) in a swimming flume in four conditions: (1) in still water, wearing a bathing suit (baseline); (2) wearing typical outdoor clothing (clothed); (3) with an additional cognitive task imposed (dual task); and (4) against a changing current (flow). Mixed methods kinematic analysis revealed four different TW coordination patterns were used across the conditions. The four TW patterns used represent a hierarchy of expertise in terms of the capacity to generate continuous lift forces, where pattern 1 (the lowest skill level) involved predominantly pushing and kicking limb movements ($N = 1$); pattern 2 was a movement pattern consisting of legs pushing/kicking and arms sculling ($N = 7$); pattern 3 was synchronous sculling of all four limbs ($N = 6$); and pattern 4 was the "eggbeater kick" (the highest skill level), with asynchronous sculling movements of the legs ($N = 9$). The four TW patterns were generally robust to the modified constraints. The higher skilled patterns (i.e., patterns 3 and 4) appeared to be the most stable coordination patterns. These results suggest that learning to perform more complex patterns to tread water might be an asset to survive in life-threatening situations.

Keywords: aquatic skills, coordination, drowning, life-saving, stability

INTRODUCTION

Drowning is recognized as a significant problem globally (WHO, 2014). Rising sea levels and unpredictable weather patterns due to climate change endanger the lives of many people all over the world (Patz and Kovats, 2002). Each drowning case is multifactorial in terms of contributing factors (i.e., preceding activity, experience, environment, task, etc.) (Croft and Button, 2015). Such factors can be thought of in terms of influential constraints that both limit and enable the emergence of behaviors – an individual's "aquatic readiness" (Langendorfer and Bruya, 1995). In that respect, treading water (TW) is a foundational movement skill for humans when submerged in water, particularly when external buoyancy aids are not available. TW involves maintaining a stable head position above the water surface by limb movements. The capacity to tread water allows people to monitor themselves and their environment and to make an informed decision about subsequent behaviors, while being able to maintain steady breathing (Golden and Tipton, 2002). While several studies have considered the mechanics of TW among skilled sports people (e.g., Sanders, 1999; Homma and Homma, 2005), less is known about how individuals of various skill levels tread water across different environmental conditions and task demands.

Schnitzler et al. (2014a, 2015) identified four main TW patterns used by individuals in still water. The four patterns were categorized within a typology from theoretically less efficient to more efficient based on the nature of forces created (lift or drag) and the type of interlimb coordination (synchronous or asynchronous) used. In order to generate sufficient buoyancy to keep one's head above the water surface, drag and lift force are the two kinds of forces predominantly generated (Toussaint and Truijens, 2005). Lift is created perpendicular to the direction of the body's movement, whereas drag acts in the opposite direction to the body's movement. Lift forces are predominantly generated through sculling (or sweeping) movements of the hands and feet. To illustrate, sculling is a "propeller" kind of movement with the hands and feet when moving the limbs outward and inward, in which the contralateral limb pairs (i.e., inter-arm and inter-leg) can act in conjoint synchrony or alternation. Furthermore, downward drag can be created with pushing and/or kicking movements. This is however less efficient than sculling, as for instance pushing downward with the arms to drive one's body upward implies subsequent recovery movements, i.e., the arms need to go upward again; the latter creates (partly) the opposite effect, namely drag in an unwanted direction (Schnitzler et al., 2014a). Therefore, TW patterns that rely upon drag force production are seen as less efficient than those that generate lift forces using sculling movements.

In their classification scheme, Schnitzler et al. (2015) showed how common TW patterns can be ranked according to their posited efficiency. Four main patterns could be identified, of which examples are depicted in the video resources associated with this article (see **Supplementary Videos**). One of the patterns (dubbed as pattern 1) implies pushing/kicking movements consisting of up and down arm movements and anterior-posterior leg movements, which can be synchronous or asynchronous (i.e., inter-leg/inter-arm coinciding movement or alternation, respectively). This technique appeared to be adopted mainly by less proficient treaders (e.g., not by experienced water polo players). Pattern 2 is a more efficient TW solution than pattern 1 (Schnitzler et al., 2014a) and it is characterized by lateral sculling movements (i.e., generating lift) of either the upper or lower limbs. A more advanced solution involves sculling of both the arms and legs (pattern 3). This pattern is relatively effective for generating lift, but due to the (synchronous) breaststroke kick with the legs when sculling, the buoyancy force produced is (partly) discontinuous. Similar to rowing in a boat, such discontinuity of force generation involves significant power losses, which can however be regained by applying asynchronous movement patterns (e.g., de Brouwer et al., 2013). Continuous generation of lift force can be achieved by using the so-called "eggbeater kick" (pattern 4). Here, the arms make sculling movements near the water surface, while the left and right legs alternate their sculling movements, forming an "alternating breaststroke kick" pattern (i.e., asynchronous inter-leg coordination). Hence, pattern 4 is most effective at generating continuous lift force to support the body and keep the head above the water surface with little up-down oscillations (Sanders, 1999; Homma and Homma, 2005). While this typology of Schnitzler et al. (2014a, 2015) was created through qualitative analysis of people TW while wearing their swimsuits in the (warm) still water of a swimming pool, most drownings do not occur in static water (i.e., swimming pools) but instead in dynamic, open water environments like oceans and rivers (WHO, 2014; Croft and Button, 2015). These environmental constraints might influence the adaptive capacities of a potential victim. The primary aim of the current study was to explore the influence of lab-controlled environmental and task constraints on the stability of TW mechanics.

Taking a radical embodied cognitive science perspective, movement patterns self-organize depending on the environment and the current state of the movement system (Chemero, 2013; Favela, 2014). According to Marsh et al. (2009), consideration of how environmental context evokes meaningful behavior is important, requiring researchers to focus "not just on the body or environment as creating input for the cognitive system, but examining a body's actions as an object of study in itself" (p. 1220). The non-linear nature of system organization means that up to a certain range of constraint level, human behavior is maintained, hence stable. Once the constraints are out of that range, sudden switching (or a transition) toward a new stable pattern of behavior can emerge (Kelso, 1995). As such, the stability of a movement pattern resides in how well it can be maintained and, hence, is reflected by when and how transitions to other patterns occur. Such transitions can lead to bifurcations or shifts (Kostrubiec et al., 2012) to a pattern more adapted to the set of constraints, as has been established within basic locomotion like terrestrial gait. For instance, at a certain gait speed (i.e., a task constraint considered as a scalable control parameter), the locomotor pattern (order parameter) shifts from walking into running (e.g., Diedrich and Warren, 1995). Furthermore, hysteresis occurs: the walk-to-run transition occurs at a higher speed than for run-to-walk due to the relative stabilities of the two types of pattern (e.g., Hreljac, 1993; Li, 2000). Similarly, for aquatic human locomotion, water flow is a well-known constraint, which also appears to be sensitive to the skill level of the swimmer (Chollet et al., 2000; Seifert et al., 2010). From a water-safety perspective, it would therefore be important to determine whether movement pattern transitions are dependent upon the proficiency of the participants in water. In other words, do more proficient water treaders have inherently more stable movement patterns that are more resistant to constraint changes than less proficient people? A related question is whether humans switch from treading water to a globally different pattern (i.e., swimming) at certain boundaries of water flow or are such transitions and hysteresis effects dependent upon the stability of the pattern that is adopted? To the best of our knowledge, such questions have yet to be investigated, so a secondary purpose of the current study was to explore whether the stability of TW patterns abides by similar dynamical principles as land-based locomotion.

Recent studies have already examined the effects of water temperature as a control parameter on aquatic survival skills (Button et al., 2015; Schnitzler et al., 2018). These experiments showed that cold environments increased the subjective and objective difficulty of the task and impacted negatively the time it could be sustained. However there was no significant modification of the TW pattern used as a function of the temperature. Other constraints could also act as control parameters in the context of aquatic survival skills. For example, Stallman et al. (2013) highlighted that clothing, water flow, or cognitive activity may also influence this motor adaptation in water. Barwood et al. (2011) examined the influence of wearing (different types of) clothing after immersion. They discovered that when dressed, an initial increase of the buoyancy (probably due to trapped air bubbles between clothing layers) gradually dissipated with time. Hence clothing constrained buoyancy differently as a function of time spent in the water. Regarding cognitive load as a control parameter, studies on land-based locomotion have shown that the primary motor task is (negatively) affected when performing a concurrent cognitive task, for example in walking (Ebersbach and Dimitrijevic, 1995; Doi et al., 2010; Ellmers et al., 2016) and obstacle crossing (Worden et al., 2016). Likewise, performing a cognitive dual task may disrupt TW movement patterns and frequency. The dual-task paradigm is a classic manipulation in cognitive science to explore the proficiency of performance on a primary task *via* the addition of a secondary cognitive task (e.g., Kirchner, 1958; Ellmers et al., 2016).

The aim of this exploratory study was to identify how the typical coordination patterns used to tread water were influenced by constraints representative of open water environments. We postulate that four different TW patterns will be identified (based on the taxonomy of Schnitzler et al., 2015). Given that TW is an important, potentially life-saving skill, we propose that the four coordination patterns may be inherently stable (i.e., resistant to external perturbation), albeit to different degrees depending on the mechanical efficiency of the preferred pattern. Hence, one might presume that more stable TW patterns are robust to perturbations and result in fewer transitions to different coordination modes than unstable patterns. Based on indications from land-based locomotion (Diedrich and Warren, 1995) one might hypothesize that there is a transition from one to another TW pattern (or even to swimming) when the water flow increases or decreases. Furthermore, when gradually increasing the current, we speculate that the transition will occur at a higher current than when the water flow speed is decreasing.

MATERIALS AND METHODS

Participants

Twenty-three participants (18–55 years of age, $F = 14$, $M = 9$) were recruited *via* advertisements placed on a university-based website and at local aquatic sports clubs. Participants signed informed consent prior to testing and were only included if they reported themselves as sufficiently competent to tread water without support for at least 5 min. Given this inclusion criterion, the TW expertise of the participants potentially ranged from competent to highly skilled (subsequently verified through qualitative analysis of movement patterns). They also completed a brief health and fitness screening questionnaire (i.e., Physical Activity Readiness Questionnaire). Exclusion criteria included: standing height of over 1.85 m (6′1′′) due to the maximal depth of the flume, self-reported learning difficulties, or existing health conditions (e.g., injuries, severe asthma) that may put the participant at risk during testing.

Equipment

Testing occurred in a swimming flume (StreamliNZ, Dunedin, New Zealand). The flume is an aquatic water channel in which the current can be manipulated from still (no flow) to 3.5 m/s. The flume depth was 2 m and a swimming area of 6 m × 2 m was available. During all conditions, the participants were recorded with four video cameras configured to cover the whole swimming area: one from the front of the swim channel, one from above, and two from the right side (see **Figure 1**). The front camera was the principal camera for analysis, the other cameras were used as back-up in case of equipment malfunction or to help confirm pattern classification. The water temperature was consistently set at 27°C to ensure the data were not influenced by temperature differences (Button et al., 2015; Schnitzler et al., 2018).

The study included four conditions: baseline (BA), clothed (CL), dual task (DT), and a water flow (WF) condition (see **Table 1**). The BA condition was conducted first, the order of the other conditions was randomized to limit order effects. During the CL condition, participants were asked to wear their own jeans, socks, trainers, t-shirt (short sleeve), and jumper (long sleeve) without hoodie or long zip. The standardization of personal clothing was an attempt to limit differences in clothing affecting buoyancy forces as shown by Barwood et al. (2011). During the DT condition, the participant had to perform an N-back memory task (Kirchner, 1958), which involved recalling whether a presented stimulus was the same as presented N trials ago (a 2-back task was used in the present study). The N-back task is a continuous task typically used to assess working memory capacity. The sequence of stimuli was presented on a TV screen in front of the participant at the edge of the flume at eye height. The verbal response of the participant was recorded by the investigator by clicking a button (if the answer was "yes") or not clicking a button (if the participant remained silent).

During the WF condition, the current of the water within the flume was modified in small increments, from still to a moving, unidirectional flow. The participants wore a belt around their chest, which was secured to a bar at the front of the flume by an elastic rope (at water level) to maintain their overall position within the flume channel. They were positioned to face the oncoming water flow approximately 4 m in front of a safety net. Previous research had shown that recreational swimmers can comfortably maintain their position by swimming in the flume at 1 m/s (Button et al., 2015). Therefore, the current was incrementally increased up to approximately 1 m/s

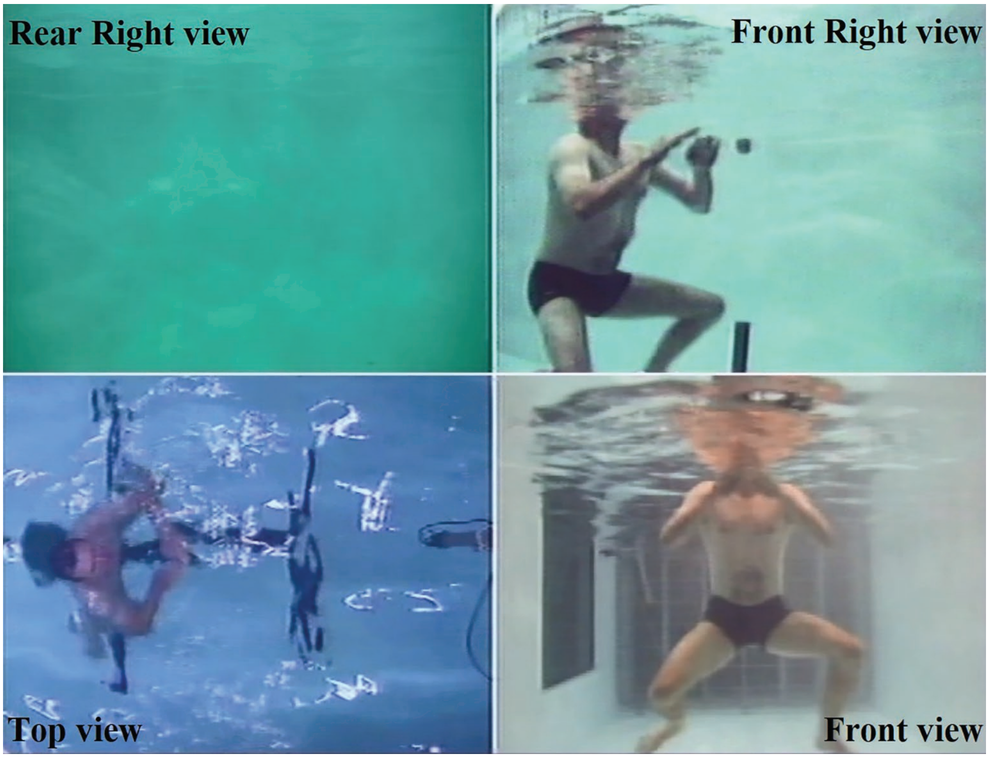

FIGURE 1 | The four synchronized camera views. The front view (bottom right image) was primarily used to determine TW pattern and movement frequency. The rear right view (top left image) was useful in instances where participants drifted from the set position and when they began swimming. These images were captured in the baseline condition. Written permission and informed consent were obtained from the depicted individual for the publication of the image.

TABLE 1 | Descriptions of the experimental conditions.

Condition	Task description
Baseline (BA)	Tread water for 180 s in still water in typical swimwear
Clothed (CL)	Tread water for 180 s in still water while wearing casual clothes (i.e., shoes/trainers, jeans, t-shirt, and a jumper) over typical swimwear
Dual task (DT)	Tread water for 180 s in still water in typical swimwear while performing the "visual 2-Back" task for 120 s, starting 30 s after the start of treading water. Participants were asked to prioritize treading water (primary task) over the performance of the 2-back task (secondary task)
Water flow (WF)	Tread water for 30 s in still water in typical swimwear. Beginning from still (no flow), the current was increased every 30 s (0-0.4-0.6-0.8-1 m/s) for 150 s and then decreased with the same increments (to 0 m/s) for a further 150 s.

and then decreased till 0 m/s, in steps of 0.2 m/s every 30 s, except for the first step (and last step), which was 0.4 m/s due to practical limitations of the flume turbines.

Procedure

This study was carried out in accordance with the recommendations of World Medical Association's Declaration of Helsinki. The protocol was approved by the University of Otago's Human Ethics Committee (Reference: 16/158). The experimental design is based on a multiple repeated measures model (baseline condition and three perturbation conditions). Before starting the experimental conditions, a number of personal and anthropometric variables were collected (i.e., height, weight, buoyancy, gender, age, and ethnicity data) (**Table 2**).

Given the potential for individual buoyancy to influence pattern stability in the current study, aquatic body weight was determined for all participants. Static buoyancy was determined in a drop tank. A plastic chair was attached *via* a strain gauge (Futek LCM300 250lb., Futek Advanced Sensor Technology Inc., USA, sample frequency: 100 Hz) to a mechanized winch that lowered the chair into the tank. Participants were asked to sit in the chair above water level with a 5-kg weight belt worn around the waist to stabilize the participant's position on the chair when submerged. The chair was then winched in the water until the participant's chin was just above water level. Once the participant and chair were steady, measurements of buoyancy (corrected for weight of participant and weight belt) were recorded for up to 20 s, while participants held their breath (to limit movement). To obtain reliable data, this procedure was undertaken three times with rests permitted between attempts.

All testing conditions (see **Table 1**) occurred on one occasion, approximately 60 min in duration. In each condition, participants were asked to tread water and keep their head position as stable as possible above the water surface (without any further instructions regarding how to move). In the WF condition,

TABLE 2 | Mean participant characteristics (±SD).

	Age (years)	Height (m)	Weight (kg)	Buoyancy (N)
Men (*N* = 9)	37.6 (10.9)*	1.75 (0.06)*	75.46 (13.46)	9.30 (0.18)*
Women (*N* = 14)	28.4 (7.1)*	1.69 (0.06)*	73.62 (17.04)	9.48 (0.16)*
Overall (*N* = 23)	32.0 (9.7)	1.72 (0.06)	74.34 (15.44)	9.41 (0.19)

**Significant difference between men and women (p < 0.05).*

participants wore a chest strap and were advised to adopt whatever movement pattern felt most comfortable to maintain their stable head position. Additional to this basic task requirement, the nature of the experimental conditions was explained to the participants in advance.

Data Analyses

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

Qualitative Analysis

Two analysts (authors CB and LB) were trained to perform qualitative analysis of TW according to the method developed by Schnitzler et al. (2014b). This method is based on the observation of different patterns of interlimb movement. According to these authors, less skilled patterns are based on the use of drag force and synchronous movements to stay afloat, whereas more skilled patterns are characterized by the use of lift force and asynchronous movements to generate small but frequent force momentum to ensure stability (Schnitzler et al., 2014b). This can be observed as upside-down (pushing) movements for the least skilled participants, whereas more skilled participants exhibit lateral movement (sculling) from the legs and the hand. Both analysts independently identified each of the four TW coordination patterns from the random sample of participants chosen. Each analyst performed qualitative analysis on a portion of the data independently and the inter-rater reliability was 100% ($\kappa = 1.0$, $p = 0.00$). This inter-rater reliability was calculated from a random sample (17%) of the data.

The predominant coordination patterns adopted in the BA, CL, and DT conditions were identified from video footage. The "*preferred*" pattern was defined as that used for the longest duration throughout each condition. Furthermore, when an additional pattern was observed for three or more movement consecutive cycles within the same condition, it was classified as a "*pattern change*." The number of pattern changes within a condition were counted and used as an indication of the stability of the main pattern. Within the WF condition, the identification of patterns was done once for every water flow velocity increment (i.e., nine times in total). Since swimming of some form was necessary at least at the highest current (1 m/s), any identifiable swimming patterns were recorded, along with the TW coordination patterns. Each velocity increment lasted only 30 s (to minimize fatigue); therefore, no pattern changes were counted within each WF bin. However, by identifying the pattern used in each step, it could be seen at which current the transition to another pattern was made.

On visual inspection, it became clear that some participants almost never changed their movement pattern, regardless of experimental condition. To check the stability of movement patterns, we could therefore *a posteriori* divide the participant pool into two subgroups ("changers" and "non-changers") based on the amount of changes made within conditions and if they used a different preferred pattern in the CL, DT, or (the first step of) the WF condition than used in the BA condition. If participants changed their movement pattern at least three or more times from the BA condition, they were allocated to the "changer" subgroup. All other participants were categorized into the "non-changer" subgroup.

Quantitative Analysis

The buoyancy data were filtered (Butterworth 4th order, cut-off frequency 0.5 Hz) and divided by the participant's weight to calculate standardized values. For the BA, CL, and DT conditions, the movement frequency of the arms and legs during treading water was determined. This frequency analysis was done by visual inspection using the video-recorded data and the average time of nine movement cycles. Three movement cycles were taken just after 30 s, three cycles just after 60 s, and three cycles just after 90 s. For the WF condition, the changing current predominantly determined limb movement frequency; hence, the frequency analysis was not performed in this condition.

Statistical Analysis

The TW patterns were initially categorized based on the preferred pattern adopted in the BA condition (i.e., patterns 1–4 according to the typology of Schnitzler et al., 2014b). Arm and leg frequency in the BA condition was compared between the four types of patterns with a MANOVA. The total number of pattern changes in each condition were also counted (i.e., the number of times there was a shift to an extra pattern and/or back to the main pattern) and participants were then allocated into two subgroups ("changers" and "non-changers"). The pattern distribution used in the two categories was compared graphically with violin plots and also with Kruskal-Wallis tests.

We were also interested in exploring whether a hysteresis effect exists for aquatic locomotion. In the WF condition, the currents at which transitions between treading water and swimming occurred were recorded and compared. A paired sample *t*-test was run to contrast the current at which the transition from TW to swimming (increasing) occurred in relation to the transition from swimming to TW (decreasing). All statistical tests were carried out using SPSS Statistics 23.0. A significance level of $\alpha = 0.05$ was adopted for all tests. Partial eta squared (η_p^2) or Cohen's *d* was reported as an estimate of effect size (Richardson, 2011) and Bonferroni-corrected *t*-tests were used as *post hoc* analysis where applicable.

RESULTS

Eighteen out of 23 participants (78%) performed all experimental conditions successfully, five were not able to and/or chose not to finish all WF stages. All dependent variables were checked for the assumptions of parametric tests and only weight did not meet these assumptions. Further analysis identified a single outlier for weight which was not removed from further analyses since the buoyancy variable was normally distributed. Mean data in **Table 2** show that males and females were different in terms of age [$F(1,21) = 6.00$, $p < 0.03$, $\eta_p^2 = 0.22$]; height [$F(1,21) = 4.61$, $p < 0.05$, $\eta_p^2 = 0.18$]; and buoyancy [$F(1,21) = 6.57$, $p < 0.02$, $\eta_p^2 = 0.24$]. However, there were no significant sex differences in terms of the patterns adopted over conditions, and the frequency of arms and legs in the BA condition. It was therefore assumed that sex did not have a significant influence upon the coordination patterns adopted and was not included in the remaining analysis.

Identification of Coordination Patterns in the Baseline Condition

The distribution (N) of participants who performed each coordination pattern in the baseline (BA) condition is depicted in the leftmost column of **Table 3**. As only one participant performed pattern 1, this participant's data were not included in further statistical analysis due to uneven group sizes. As can be seen from **Table 3**, movement frequency of the legs differed between patterns [$F(2,19) = 9.89$, $p < 0.01$, $\eta_p^2 = 0.51$]. *Post hoc* tests confirmed that leg frequency was higher in pattern 4 compared to patterns 2 and 3 (Bonferroni: $p = 0.002/p = 0.01$, respectively). There is also a tendency for higher arm frequency in pattern 4 compared to patterns 2 and 3 with an effect size considered as small (Cohen, 1988), but this trend failed to reach significance [$F(2,19) = 3.25$, $p = 0.061$, $\eta_p^2 = 0.26$].

Influence of Constraints Upon Coordination Patterns

In the BA condition, five participants made changes to their TW patterns (**Table 3**). On the basis of whether participants made pattern changes from their preferred pattern in the CL and DT conditions, two more participants were identified as "changers" ($N = 7$, 30%). Kruskal-Wallis tests identified differences in coordination patterns between the subgroups in the CL condition [$\chi^2(1) = 5.85$, $p < 0.05$, $\eta_p^2 = 0.23$] and the WF condition [$\chi^2(1) = 4.52$, $p < 0.05$, $\eta_p^2 = 0.17$]. The seven changers tended to use less efficient TW patterns (i.e., mostly pattern 2) compared to the non-changers subgroup (mostly patterns 3 or 4) (**Figure 2**).

TABLE 3 | Average movement frequency of arms and legs (±SD) and the total number of pattern changes in the baseline condition (BA).

	Arms (Hz)	Legs (Hz)	Pattern changes
Overall ($N = 23$)	0.79 (0.22)	0.80 (0.25)	28 ($N_c = 5$)
Pattern 1 ($N = 1$)	0.71 (0.00)	0.83 (0.00)	7 ($N_c = 1$)
Pattern 2 ($N = 7$)	0.74 (0.26)	0.63 (0.13)*	9 ($N_c = 2$)
Pattern 3 ($N = 6$)	0.66 (0.23)	0.68 (0.24)*	12 ($N_c = 2$)
Pattern 4 ($N = 9$)	0.92 (0.12)	1.01 (0.18)*	0 ($N_c = 0$)

*N_c depicts the number of participants that showed within-condition pattern changes.*Significant difference between pattern 4 and either 2 or 3 in leg frequency ($p < 0.05$; Bonferroni: $p = 0.002/0.010$, respectively).*

Three out of 23 participants (13%) changed TW pattern within the CL condition compared to their preferred BA pattern. Interestingly, there were fewer overall pattern changes in the CL condition as compared to the BA condition (18 vs. 28 in total). Furthermore, only two participants (7%) changed their TW pattern in the DT condition compared to the BA condition. There were only eight changes within the DT condition, compared to 28 within the BA condition. Although not reported here for brevity, analysis of the N-back cognitive task revealed minimal decrements in the performance of the secondary task (maintained at between 100 and 90% for all but one participant).

In the WF condition, all 18 participants (who completed this condition) started using one of the four patterns listed in **Table 3**. When the water started to flow, only four participants (22%) changed their TW pattern before starting to swim. No clear order of swimming techniques (breaststroke and freestyle) was used at the higher currents, since some participants started with breaststroke and then freestyle, while others only used breaststroke or freestyle. In **Figure 3**, the overall course of movement pattern transitions is shown. As expected, all participants changed their movement from TW to swimming when the current increased and back to TW when the current decreased. Overall, there were 58 transitions between patterns in this condition with each participant making between two and four changes.

The transition current was different between the increasing and decreasing flow [$T(17) = 8.79$, $p < 0.001$, Cohen's $d = 2.1$]. The transition tended to occur at a higher current (mean = 0.72 ± 0.10 m/s) in the increasing current condition than when the current was decreasing (mean = 0.40 ± 0.18 m/s). Participants who changed from either pattern 2 or pattern 3 to swimming transitioned at the same or higher current than from swimming back to TW. However, for individuals performing pattern 4,

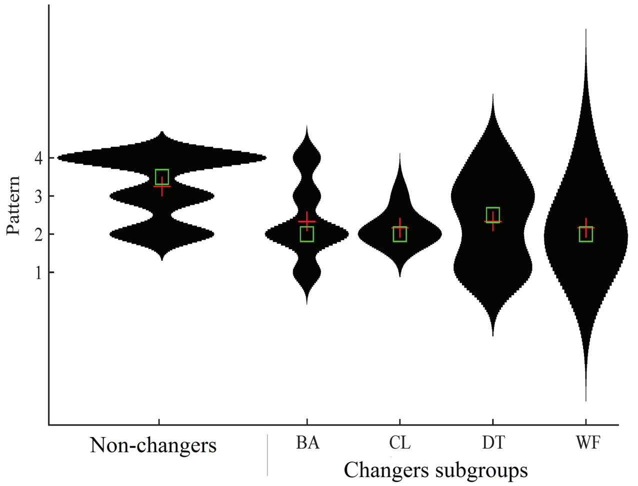

FIGURE 2 | Violin plots of TW pattern distributions for the Non-Changers and Changers subgroups. The green boxes denote the median and the red crosses denote the mean average. The wider the shape, the more frequently the TW patterns were expressed. The longer the shape, the larger the interquartile distribution.

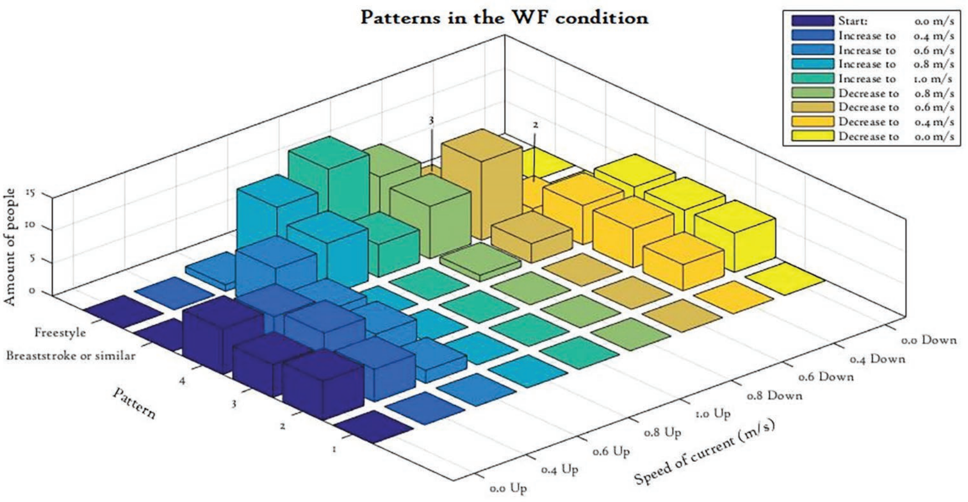

FIGURE 3 | 3D bar chart depicting shifts to other TW patterns, breaststroke or freestyle in the WF condition.

this group effect was not the same since they were already treading water at 0.8 m/s with decreasing current, while there were no such patterns present at 0.8 m/s with increasing current (indicative that the hysteresis effect is inversed for pattern 4).

DISCUSSION

This exploratory study considered how TW patterns were adapted to altered task and environmental constraints. In general, the results suggest that people use robust TW movement patterns that do not easily change to other patterns when constraints change. Overall four TW patterns were identified (**Table 3**), in line with past studies (Schnitzler et al., 2014a, 2015). The stability within conditions seemed highest among the nine individuals (39%) performing pattern 4. Furthermore, the eight participants (35%) using the least efficient patterns (patterns 1 and 2) displayed more transitions within and between conditions (**Figure 2**). It therefore seems that participants using pattern 4 were the least vulnerable to disruptions and that this "eggbeater kick" would be the more stable coordination mode that is resistant to changes in constraints. The radical embodied cognition approach to behavior emphasizes how humans learn to move adaptively as constraints change (e.g., Chemero, 2013) and this study provides another excellent illustration of this phenomenon.

In the current research, we explored the effects of a (continuous) cognitive demand on TW performance by using a dual task. However, the dual task did not disrupt the TW patterns (since changes were less frequent in the DT than the BA condition) and the performance of the dual task was not harmed either (>90% correct on average). Previous research on land-based locomotion had indicated that the performance of the primary task (i.e., walking) can be disrupted by the addition of a secondary cognitive task (Ellmers et al., 2016). One interpretation of this discrepancy is that primary task activities that are visually guided (like walking) are more vulnerable to dual-task disruption than those that do not rely heavily on continuous visual regulation (like TW). Another possible explanation is that participants were able to freely switch attention between the dual tasks without significantly disrupting performance of the coordination pattern used in the primary task (see Verhaeghen and Basak, 2005). Since pattern changes in the DT condition were less frequent than in BA, the DT condition in this research might serve more like a real-life "baseline," since individuals typically do something else while TW (e.g., talking or planning their next behavior). The BA condition of this research might have been too monotonous, which invited individuals to explore (see Newell, 1986) and try out other ways to tread water and therefore more shifts in the BA condition than in DT resulted. Furthermore, in real-life drowning situations, typical dual task scenarios would likely be much more demanding (i.e., planning a survival strategy, weighing up risks against benefits, etc.) and anxiety levels would be higher than during the DT condition of this study.

It was notable that changes in coordination do occur when the current of the water alters. Rather than transitioning from TW to swimming due to spatial restrictions of the flume, we believe that participants change because it becomes a more streamline (efficient) position to comfortably adopt in the moving water. Movement patterns of low stability levels are more vulnerable to transitions as has been shown for example in human hand movements (e.g., Kelso, 1984; Haken et al., 1985) and locomotion on land (e.g., Hreljac, 1993; Diedrich and Warren, 1995; Li, 2000). Individuals performing the eggbeater pattern (pattern 4) were able to maintain treading water in faster flowing conditions compared to individuals performing the other TW patterns (**Figure 3**). However, note that these pattern transitions due to water flow were mainly changes between treading water and swimming, not (often) between the four different TW patterns.

Not only did individuals using pattern 4 maintain it at higher speeds in the WF condition, they also made no changes within the BA condition and were more often categorized in the non-changers group. We interpret these findings as indicative of greater relative stability in pattern 4 compared to the three other patterns. Nevertheless, the movement frequency of the legs was higher compared to the other patterns (**Table 3**), so pattern 4 might be more physically demanding. As the asynchronous sculling of legs putatively generates smaller lift forces (albeit continuously) in contrast to the synchronous pattern 3, a quicker cycling action (i.e., a higher movement frequency) is required to maintain the head position above water. Consequently, if in a survival situation an individual needed to tread water for extended periods of time, the more stable pattern may not necessarily be the most efficient pattern to adopt. It is also likely that the stability of this pattern might be related to specific experience, since pattern 4 is often used by water polo players and synchronized swimmers (Sanders, 1999; Homma and Homma, 2005). It will be important for future research to compare the relative benefit to be gained from using the different TW patterns particularly in terms of energy efficiency and past experience. Additionally, an important future consideration will be the extent to which vertical and horizontal transfer exists between skills such as treading water and associated activities like swimming.

Our results also show for the first time that a hysteresis effect may exist between TW and swimming, which is mediated by TW expertise. In more detail, the transition from TW to swimming tended to occur at a higher current than when switching back to TW in patterns 2 and 3 (see **Figure 3**), whereas the transition from TW to swimming in pattern 4 occurred at a lower current than when switching back to TW. One interpretation of this indicative finding is that pattern 4 possesses more inherent stability than the other three patterns and is more resistant to the external perturbation of water flow. Further research is needed to formally model and confirm the indicative hysteresis effect more thoroughly than we have been able to in this exploratory study.

The design of the study and limited instructions provided helped to characterize the intrinsic dynamics of the participant's behavior in an ecological situation. Importantly, participants were not told how to tread water but simply to maintain a stable position in the water. Had we instructed participants to resist transitions between patterns as long as possible, then different behaviors might have resulted, but that was not the main focus of the study. This analysis of emergent behavior is typical of previous dynamic systems research and extends land-based treadmill studies to aquatic locomotion (e.g., Kelso, 1981; Kelso, 1984; Diedrich and Warren, 1995). Still the question remains: do we need to change patterns to be able to cope with the different aquatic circumstances regarding dynamic, open water environments? A few participants mentioned that they started to swim in the WF condition just because the flume eventually had an "end" (safety net) to avoid, which may not be the case when immersed in a river or sea. Therefore if in open water, these participants mentioned they would just go with the flow and keep themselves afloat. Resisting a current might not be the most effective strategy to survive (e.g., when caught in a tidal rip), but keeping the head above the water and not panicking does seem important, whether you "go with the flow" or not.

Limitations

In this study, we tried to recreate typical constraints that might affect the capacity for people to tread water in open water situations. However, closely simulating all features of open water situations in a flume was not possible. In open water, there is no need to stay at the same place in the current most of the time, but due to material conditions of the testing environment the participants had to avoid moving toward the end and sides of the flume. While the spatial restrictions imposed may have admittedly influenced behavior (as they undoubtedly do in treadmill locomotion), the control procedures employed were necessary for logistic and safety reasons. It is also possible that fatigue may have influenced whether participants made transitions between patterns particularly among less skilled participants. As fatigue was not a focus of this investigation (albeit an important topic worthy of future consideration), the procedure was designed to limit the amount of time exercising in each condition to no more than 5 min and with ample opportunity to rest between conditions. Furthermore, anxiety undoubtedly plays an influential role in most survival situations, but for ethical reasons fear could not be induced within these controlled laboratory-based settings. Lastly, buoyancy forces will vary among the population for example due to different weather conditions and clothing worn (Barwood et al., 2011). For comparison between participants, a standard set of clothing was imposed, but that limits generalization to all immersion situations in which clothing is varied. Despite such limitations due to the testing conditions, it is important to know the potential disruptions typical constraints can have on TW. This knowledge will help in further research about the prevention of drowning.

Practical Implications

This study suggests that different TW patterns may be expected from the general population and that such movement patterns are fairly robust to different circumstances. Some patterns are more effective at generating lift force and resisting the influence of altered constraints. We showed that the "eggbeater kick" was the most stable pattern although it is not necessarily the easiest (most familiar) pattern to produce. The leg kick lateral sculling movements and asynchronous coordination thereof may mean that this pattern requires considerable practice and instruction to perform effectively. When designing a representative training environment, water safety instructors should try to enrich practice with different sets of constraints, i.e., by asking trainees to tread water in different directions at different speeds and with and without clothing. As cognitive function does not seem to be hampered by treading pattern, it seems advisable to create scenarios that promote problem solving and decision-making while practicing TW. Finally, it is important to note that a stable movement pattern could be life-preserving in a threatening situation.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Human Ethics Committee, University of Otago. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CB conceived the experiment, co-supervised LB's Master's project, and wrote the final draft of the article for submission. LB conducted the data collection and data analysis and lead wrote the first draft of the article. CS provided advice on qualitative analysis and data interpretation, as well as editing the final draft. HP instigated the project by organizing LB's project in New Zealand, provided advice on experimental design, and also edited the final draft.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2019.02579/full#supplementary-material

SUPPLEMENTARY VIDEO 1 | Exemplary video of treading water pattern 1 according to the classification scheme of Schnitzler et al. (2015).

SUPPLEMENTARY VIDEO 2 | Exemplary video of treading water pattern 2 according to the classification scheme of Schnitzler et al. (2015).

SUPPLEMENTARY VIDEO 3 | Exemplary video of treading water pattern 3 according to the classification scheme of Schnitzler et al. (2015).

SUPPLEMENTARY VIDEO 4 | Exemplary video of treading water pattern 4 according to the classification scheme of Schnitzler et al. (2015).

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Cultural Artifacts Transform Embodied Practice: How a Sommelier Card Shapes the Behavior of Dyads Engaged in Wine Tasting

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The radical embodied approach to cognition directs researchers' attention to skilled practice in a structured environment. This means that the structures present in the environment, including structured interactions with others and with artifacts, are put at least on a par with individual cognitive processes in explaining behavior. Both ritualized interactive formats and artifacts can be seen as forms of "external memory," usually shaped for a particular domain, that constrain skilled practice, perception, and cognition in online behavior and in learning and development. In this paper, we explore how a task involving the recognition of difficult sensory stimuli (wine) by collective systems (dyads) is modified by a domain-specific linguistic artifact (a sommelier card). We point to how using the card changes the way participants explore the stimuli individually, making it more consistent with culturally accrued sommelier know-how, as well as how it transforms the interaction between the participants, creating specific divisions of labor and novel relations. In our exploratory approach, we aim to integrate qualitative methods from anthropology and sociology with quantitative methods from psychology and the dynamical systems approach using both coded behavioral data and automatic movement analysis.

Keywords: embodiment, embodied learning, cultural transmission, artifacts, interpersonal coordination

> "We join ourselves to the living world by the artifacts of art and science – by made things"
>
> Wendell Berry, *Life is a Miracle*, p. 83

INTRODUCTION

In the ecological psychology approach, the forces shaping behaviors and skills are thought to belong to the structured environments and to individual adaptations and tunings to these environments, with both having equal importance. Behavior is guided by affordances, which are relational properties. Thus, they are neither properties of the world nor of the organism but, rather, are "relations between the abilities of animals and features of the environment" (Chemero, 2003, p. 189). Often in psychological explanations, however, the explanatory thrust is aimed at the individual cognitive processes and structures, while the recognition of the role of environment is left to anthropological or ethnographic studies. Recent developments in embodied, distributed, and situated cognition have changed this situation, resulting in a substantial body of integratory work (Hutchins, 1995, 2006; Cannon-Bowers and Salas, 2001; Fowler et al., 2008; De Jaegher et al., 2010; Cooke et al., 2013; Hasson and Frith, 2016; Fuchs, 2017; Di Paolo et al., 2018). Following and elaborating these approaches, we present a study in which we aimed to recognize the role of an element of the environment, a culturally constructed professional artifact, in shaping individual and collective behavior.

We advocate a systemic approach, in which the structures of the environment (including artifacts and others' behavior) are treated as constraints on systems' dynamics, able to influence these dynamics on multiple levels and leading – in specific cases – to new functional organizations. Within this approach, learning individual skills encompasses processes on many time scales and is contingent on organizing through niche construction. Thus, learning on a slower time scale includes making artifacts, such as protocols, tools, machines, and sports equipment, that ratchet the learning process by acting on individuals, shaping their actions and interactions. Such ritualized interactive formats and artifacts can thus be seen as forms of "external memory," cues to the "right" ways to do things, usually shaped for a particular domain. They constrain skilled practice, perception, cognition, and interaction, allowing for effective collaborative actions across groups and time spans due to their form (i.e., how they are stabilized and designed) and, importantly, due to agents' tuning-in to social affordances, which enables their use (e.g., Schmidt, 2007; Marsh et al., 2009). Social roles and norms restrict affordances associated with the physical properties of objects by designating who can undertake a certain action on the object and when or which actions are considered appropriate or inappropriate (Schmidt, 2007). The goal of this work is to show the utility of such systemic thinking about artifacts in skillful performance and propose ways to measure their active involvement in shaping both the results and the actions and interactions themselves.

Our study is a follow-up analysis of an earlier study by Zubek et al. (2016), which aimed to measure the collective gain in the recognition of difficult sensory stimuli. The collective gain was expected to result from interaction with another participant and/or with an artifact designed specifically for the description of the stimuli. In that study, the participants learned to recognize and distinguish several wine types, either individually or in pairs, with or without the aid of a sommelier card. The results showed interesting differences in performance between the pairs using the artifact and those not using it. A quantitative approach using bias-variance analysis showed a marked decrease in the variance of responses given by pairs with the card and a slight, albeit non-significant, benefit in performance. In the present research, we focus on the influence that the presence of the card exerted on the process of performing the task. Therefore, we compare the systemic behavior of pairs using the card with that of pairs with no card, analyzing the dyads' behavior both on the individual and collective levels.

As mentioned above, in our investigation of the sommelier card's role in collective tasks, we adopt a systemic perspective, striving to integrate psychological, anthropological, and sociological approaches. Therefore, we perceive wine recognition not only as a cognitive task but, equally importantly, as a culturally embodied practice. Likewise, we view the sommelier card not only in terms of its surface linguistic content, processed by individuals, but also as a cultural artifact that embodies the knowledge and experience of past generations of sommeliers and that is itself a structured physical object able to influence individuals and their interactions. There are understandable difficulties with portraying such influences in their full complexity. A standard experimental methodology requires defining variables and measures before performing any experimentation to enable objective judgment of the experimental outcomes. In the original study by Zubek et al. (2016), the interpretation of the two factors – the presence of an interaction partner and the presence of a sommelier card – became difficult because it was not known how the card altered the way in which people worked together. The interactions of the dyads who used the sommelier card could have had an internally different structure and meaning than the interactions of the dyads without the card, raising a question if a simple linear effect of a "presence of interaction" factor captured this change accurately. In the present paper, we combine qualitative intuitions with quantitative analysis to explore this issue. We adopt a dynamical systems theoretical framework, which allows for a pluralistic account of complex phenomena using multiple levels of description (Abney et al., 2014; Witherington, 2015).

In our case, we observe the relevant phenomena on the level of sequences of qualitatively coded individual behaviors, on the level of the coordination of behaviors, and on the level of automatically extracted movement measures. In addition to observing specific changes (e.g., an increase in the frequency of certain behaviors), we strive to reconstruct general systemic properties from a set of interrelated variables participating in the interaction-dominant systemic dynamics (Van Orden et al., 2003). We thus explore the patterns of individual and interactive behavior in terms of their stability, variability, and complexity using specific methods of time series analysis: information-theoretic measures of transition probabilities (Cover and Thomas, 1991; Papapetrou and Kugiumtzis, 2013) and recurrence quantification analysis (Marwan et al., 2007). Using these methods, we are able to describe systems' dynamics in both qualitative and quantitative terms, including many different facets of the influence of the cultural artifact. We seek to illustrate the versatility of this approach based on the wine recognition task as the model of a cognitive embodied collective task.

The structure of the paper is as follows: In the section below we establish an integrative theoretical framework for considering the role of artifacts in collective tasks. This framework allows us to formulate our research questions, concrete hypotheses, and exploratory goals. In the section "Our Study" we briefly describe the original study, with its analyses and results, and operationalize our questions and hypotheses within its context. The section "Materials and Methods" is devoted to the procedures and methods used in this study for data coding and analysis. The section "Results" describes the outcomes of the analyses on the individual and collective levels. We conclude with a discussion, conclusions, and further prospects.

The Role of Artifacts in Distributed Cognitive Systems

The embodied, distributed, and situated approaches to cognition, resonating with earlier thought in anthropology and sociology, allow for a change in the conceptualization of objects present in the environment, especially artifacts. In contrast to regarding them as objects of perception whose properties have to be represented in an individual's knowledge in order to exert their influence on behavior, they can be treated as carefully, culturally shaped constraints, having a much more immediate impact on action and interaction. This reconceptualization of objects with respect to social relations is apparent in recent anthropological and sociological works, which we briefly refer to below. We argue that connecting these works more closely with the ecological psychology views on perception and action, especially with recent developments in the field regarding social affordances, is especially promising in making the picture more complete, resulting in concrete, sensible measures, and testable predictions.

In anthropology, the "agency" of things seems more readily recognized than in most approaches within cognitive psychology. It is acknowledged that things can influence the construction of a human identity and relationships with others and with the environment. They are considered "unknown actors" or "silent things," i.e., subjects with a kind of agency similar in some respects to that of the owners of a unique subjectivity (Olsen, 2003). Considering the role of cultural artifacts and their agency is crucial for understanding the social world. Going even further, in sociology, Bruno Latour's actor-network theory describes the world from the perspective of the relations between artifacts and humans, treated equally as actors in the network (Latour, 2005, pp. 46, 52–53). Things can become social actors as long as they influence social reality. Thus, their agency is premised on their presence changing the behavior of their users and the relations among them.

Obviously, the agency of a thing remains incomparable to the agency of a human or, more generally, a living being, as it is crucially dependent on other elements of a cognitive system and its context (Van Oyen, 2018). However, such approaches take us beyond the traditional psychological theoretical tendency to regard objects as passive sources of "input" shaping behavior only because of how they are represented. This prompts more quantitatively oriented researchers to seek operationalizations for the "agency of things" within composite cognitive systems and on multiple time scales.[1] This is consistent with recent developments toward embodied and distributed theories of cognition, whose approach to the role of artifacts we consider next.

Most of the above accounts are in agreement that an object may have a form of agency only by virtue of its existence within a social reality as it affects the behavior of and relations among the people interacting with it. While anthropological, archeological, and sociological approaches focus on longer time scales, showing how material things shape the way societies and cultures develop and sustain themselves (Ingold, 2013; Malafouris, 2013), cognitive science tends to focus on the online influence on behavior. Within the perspectives of extended (Clark and Chalmers, 1998) and distributed (Hutchins, 1995) cognition, objects are considered constituent parts of cognitive systems. Congruently with the abovementioned sociological approaches, objects can be taken to constitute agentive elements with the ability to change important properties of the system's organization and relations with the environment. This is possible because artifacts exert specific constraints, enabling or limiting the actions of other elements within a distributed system.

Consider the example of a tightrope walker carrying a balance pole. Carrying the pole increases rotational inertia and lowers the center of gravity. This is beneficial for the walker because these changes in the physical properties of the system make the balancing act easier. To gain this benefit, the walker needs to interact with the artifact appropriately: in this case, the pole must be held steady in the center. The pole may be further adapted for such use by marking its center in some visible way. Thus, the task of tightrope walking is realized by a joint pole-walker system. A walker learning to use the pole is effectively adapting to specific environmental conditions – a form of niche. The pole itself can be adapted (e.g., by marking the center, adjusting the length), which is constructing a cognitive niche (Laland et al., 2000; Clark, 2006) in a way that reflects past walkers' experience.

A sound theoretical basis for the study of such distributed systems is provided by Hutchins (2010), who proposes viewing human cognition as an activity that arises from the interaction of a cognizer with the social and material environment. Cognition is very often conducted in the presence of other human beings while using various tools – maps, diagrams, tables, calendars, and models of different kinds. These tools are cognitive artifacts (Hutchins, 1999) in the sense that they were created to aid or improve cognition. However, they not only facilitate cognition but are also able to lastingly transform cognition and enable that transformation to become embedded in the culture. A simple, very old example of a cognitive artifact is the abacus, which aids numerical operations such as addition and multiplication. Even though much faster and more precise tools such as calculators already exist, very often schoolchildren are taught a multiplication table with the use of the abacus. The reason is that it can transform

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[1] An additional asset of focusing on such frameworks is that they diminish the gap between cognitive approaches and the social sciences: "Because cognitive structures need not exist only in the mind [and perhaps never do so, if the radical version of d-cog (distributed cognition) is correct], but instead can exist in the complex interactions of social groups and technological artifacts, one can study social groups cognitively, or cognitive systems sociologically. There need be no unbridgeable divide between social and cognitive explanations" (Brown, 2011, p. 21).

multiplication from a simple recollection task to a spatial reasoning exercise, which can later help children to understand notions of area and dimensionality. Although such artifacts are termed "cognitive," it is the embodied practice that transforms cognition. Tactile interaction with the abacus facilitates embodied understanding of the concept of a measurement unit as well as how to correctly place it in the coordinate system. Another example, given by Hutchins, is culinary art, which is a skill that involves the use of various interactively shared and developed tools – cookbooks, kitchenware, nutrition tables, food-pairing or presentation techniques, and more. A novice cook acquires culinary skills in interaction with these cognitive artifacts, which shape the way cooking is practiced, and in interaction with more experienced chefs using those tools. On the other hand, beginner chefs are encouraged to experiment on their own and come up with novel recipes and practices that may revolutionize the entire field – again, often ratcheted not only by working out new practices but also new artifacts.

The full picture of a "human vs. human vs. object (or artifact)" interaction is captured by the model that Hutchins (2010) calls "a square-cut gem of interaction" (**Figure 1**). In this view, a multimodal interaction system is distributed across members of a social group whose cognitive process arises from the coordination of their bodies and communication in relation to the external world, including artifacts. Social organization, on a par with the organization of the environment, determines how information is transmitted between group members and thus may itself be viewed as providing architecture for cognition (Hutchins, 2001, 2006). On the other hand, a tool can be incorporated in the way people perceive and control common actions (Hutchins, 2010).

These approaches are very helpful for understanding the roles of niche construction and the distributed and multi-scale nature of cognition involving artifacts, but they usually do not provide details on how artifacts exert their influence. How are behavior and relations affected in each instance of the artifact's use, and which past, historical processes make such influence possible? Ecological psychology, we believe, is of much help here, as it describes objects, including artifacts, in terms of affordances, relational properties that directly specify the behaviors of cognizing systems. Learning, in this framework, consists in tuning to specific affordances of objects and the niche, changing the behavior of an agent and the agent's direct perception (e.g., Dreyfus, 2002).

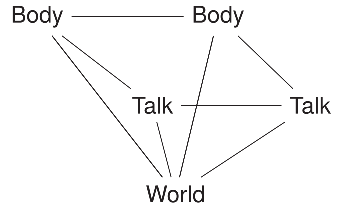

FIGURE 1 | Square-cut gem of interaction (see Hutchins, 2010). In the wine tasting ritual, the sommelier card influences all the relationships specified by the square-cut gem of interaction. It provides language describing the external world of wines' aroma and flavor that enables tasters to communicate and compare their sensations regarding the wine. Conversely, it also shapes these sensations by providing evaluation categories that the taster would never come up with him- or herself.

In the case of artifacts, learning involves both an online, individual, as well as collective and social scales when an artifact is embedded into a network of social routines (Schmidt, 2007). Through the predictable re-enactment of the social "game," objects also gain social meaning, providing for the emergence of particular roles in social interactions. The use of an artifact in a given situation will thus be contingent on culturally evolved social routines. Thus, how an artifact is exerting its power would be excessively difficult to explain when resorting only to the individual's knowledge regarding how to use it. Much of the artifact's power lies in – often tacit – reactivation of specific behaviors in social routines, influencing the projects we are constantly engaged in (Merleau-Ponty, 1962). These are real physical events occurring in concrete situations and should be visible as constraints, both on the individual behavioral dynamics and at the level of collective systems. Moreover, the effects of these constraints can be assessed quantitatively with respect to how the presence of an artifact impinges on the behavior of a system: this consists in comparing a distributed system without and with an artifact in terms of the organization of its elements and of the whole. Such understanding creates the possibility of studying the "agency of things" in a more structured and quantitative way, using the methodology of complex systems. Changes can be captured over multiple time scales: slower ones, when social relations are shaped into strands of organized activities and artifacts are shaped through design, and faster, online processes, when the presence of the artifact can directly impinge on perception and action.

In our study, we will use this framework to investigate the online influence of a sommelier card on distributed cognitive systems for recognizing wines. The card is treated as an enabling constraint whose physical presence impinges on individual behavior and shapes interactions through the physical and social meaning it carries, effectuating measurable changes through the presentation of physical and social affordances. We will seek to measure and explore the changes in the distributed cognitive system, studying the organizational properties of its elements and of the whole rather than delving into the cognitive processes and representations of individuals. We believe this to be an informative complementary perspective to gain insights into the cognitive properties of the novel distributed systems created by people interacting with and without an artifact. We also ask if there is a way to gauge the "agency" of the sommelier card both through its effect on the individual participants and through its influence on the relations among the system elements and thus the entire system organization.

Our Study

In this work, we analyze a subset of results from the previous study of Zubek et al. (2016), which concerned the impact of language on performance in a perceptual learning and recognition task. In that study, language influence consisted of the online linguistic interaction of the participants as well as their interaction with a sommelier card, which is a culturally designed professional linguistic artifact for wine description and recognition. The card was a slightly simplified Polish version of the Associazione Italiana Sommelier card, which, for several years, has been used among the Polish sommeliers. This means that the key dimensions used in the card had the Polish terms agreed upon by the Polish sommeliers and used in professional writing (for details, see Zubek et al., 2016). The task of the participants was first to learn the taste (and smell) of three wine samples and then to recognize these wines among a larger set of wines. The experiment had a classic 2 by 2 factorial design: the participants performed the task either individually or in pairs (free online linguistic interaction) and with or without the aid of a sommelier card (constrained linguistic interaction). Accuracy of recognition in each condition, as well as the structure of errors, was studied as a function of the type of "cognitive system" created in each condition: individual, individual with card, dyad, and dyad with card.

In terms of task performance, Zubek et al. (2016) observed that while recognition as such was mostly unaffected, bias-variance decomposition (Gigerenzer and Brighton, 2009) revealed differences between the groups. In pairs that used the sommelier card, the variance component of the error was decreased compared to that in the other groups. Moreover, the behavior of participants performing the task solo seemed to be largely unaffected by the card. Following the analyses of Fusaroli et al. (2012), the authors of the 2016 study performed linguistic analyses of verbal interactions between the participants. They analyzed the vocabulary used by the participants, focusing on the words used to describe the wine. The analysis revealed that the vocabularies of group members using the card had more words in common than those of participants in the "no card" group, and these vocabularies were more concise, as indicated by the smaller type-to-token ratio (i.e., the ratio of vocabulary size to all uttered words).

Zubek et al. (2016) thus demonstrated that the presence of the card had a structuring influence in streamlining people's vocabulary and decreasing the variance in dyads only. This prompted us to look more closely at the effects of the sommelier card on the joint behavior of the participants. Consequently, in the present study, we focus on the activity of performing the task itself rather than on participants' wine-identification performance. We see this activity as a goal-driven, embodied interaction between two people in two conditions: an unstructured interaction and an interaction structured by the sommelier card. Integrating the psychological and anthropological approaches to cultural artifacts, we acknowledge the agentivity of a card as an element of a distributed cognitive system, operationalized as its ability to change individual behaviors and create novel relations among participants. Adopting a dynamic and systemic perspective allows us to measure this constraining influence quantitatively as a change in individual cognitive systems embedded in a larger collective system. The influence can be gauged in terms of ordering based on (i) the timing and coupling of qualitatively coded behaviors at the individual and dyadic level and (ii) more global measures of automatically coded motion patterns.

Hypotheses

The sommelier card is a cultural artifact, a condensate of knowledge and practical experience exerting constraints on wine tasting practice and the product of the expertise of generations of sommeliers. It contains vocabulary that streamlines the talk of the participants, but it also contains an implicit structure, such as the ordering of sensory descriptions (from visual to olfactory to taste characteristics). It is also a physical object in the cognitive system to which both members of the system can refer. It is thus a constraint that can work on several levels of organization, changing the embodied individual and interactive behavior of the participants and the relation between them in a larger collective system.

Adopting a dynamical systems perspective, it is useful to think about the relevant cognitive systems in interaction with the card in terms of the degrees of freedom and constraints that it may impose. Each system has a characteristic number of degrees of freedom, which means that its behavior may vary freely in certain dimensions. Adding constraints should decrease the number of degrees of freedom, which may introduce order in the behavior, consequently reducing the system's variability, or which may allow new stable behaviors to appear, thus increasing the system's variability (so-called enabling constraints). Thus, our general analytical strategy is to measure the behavior of systems with and without a card and to compare their variability and the coupling strength of their elements in various dimensions related to the wine recognition task and communication between participants.

The artifact can influence individuals' strategies for exploring the wine to be recognized, perhaps prompting them to fall into the patterns of more skilled sommeliers. We thus expect a change in the frequency distribution of exploratory behaviors and their ordering (frequency of transitions). At the collective level, the card, as a physical object in a shared space, may impose additional constraints on the strength of coupling of behaviors. In both cases, we expect more ordering and thus lower entropy of behavior, both as analyzed on the level of meaningful actions and on the level of the interactants' movements.

More concretely, at the individual level, the proportions of each event (action) type are expected to gravitate toward the patterns exhibited by more experienced sommeliers. The visual modality was not available to the participants as a recognition cue (in the learning phase, wine was served in black wine glasses to minimize reliance on color, as this would render the task too easy); thus, we expect (i) a change in the proportion of drinking vs. smelling behaviors (the latter is required by the wine descriptors included in the card but is not typical for amateur tasters). Moreover, we also expect (ii) a change in the sequences of actions, i.e., which type of event is likely to follow another. While it is difficult to state beforehand what transitions in particular will increase or decrease in frequency, we assume that in the absence of the artifact, the sequences will be more unstructured, resulting in a more uniform distribution of transition types. The card, on the other hand, is expected to induce the participants to repeat certain sequences of events more often than others, the ordering within sequences being influenced by the ordering of the modalities on the card. We are open also to the possibility that the coding process, which forces detailed observation of the qualitative aspects of the participants' actions, can bring further insights and research questions.

At the collective level, we should also see the structuring effect of the artifact. Here, however, our research is more exploratory. In general, the card, as one more physical element in the shared conceptual and physical space, could act as an additional constraint, introducing order in the behavior of a system as a whole and particular types of coupling (such as the emergence of leader-follower dynamics, where one participant becomes the reader of the card and initiator of behaviors). This may be observed at the level of the analysis of correlative structures of behavior as well as at the level of physical movement, which often reflects such social structures (see Fowler et al., 2008; Paxton and Dale, 2013). Conversely, a card can act as an enabling constraint facilitating the division of labor, such as the "delegation" of a certain modality to a single member of the dyad or the delegation of a card-reader. We explored these possibilities and related the properties of the dyads as systems both to their performance and to the participants' satisfaction with the interaction.

MATERIALS AND METHODS

Procedure

The experiment was conducted following the ethical guidelines for psychological research and approved by the local ethical committee of the Institute of Psychology, Polish Academy of Sciences. The participants, upon arriving, were assigned to one of the four experimental conditions: individual or dyad, with or without a sommelier card. The assignment was random, the pairs themselves were created by convenience from the participants who were available (in most cases, the participants in the dyads did not know each other; see **Table 1**). For both the individuals and the dyads, the task was to learn the smell and taste of three different wines (learning phase), and later, after a 40-min break filled with non-verbal tasks, to recognize these wines among other wines (recognition phase). In the learning phase, the three target wines were presented in black glasses labeled 1, 2, and 3; the labeling was consistent for both participants in the pair. The instruction was to remember the wines for the recognition task, which will take place later. Moreover, in this phase (and only in the condition with the cards), three copies of a sommelier card were introduced (see **Supplementary Materials**). The participants had to fill them out with descriptions of the three wines. The participants were instructed to rely on their own, colloquial understanding of the terms on the card; no additional explanation was provided. In the recognition phase, the participants were given six wine samples (coded A to E; coding was consistent within each pair), among which the initial three target wines were present. They were to point them out and mark them with their original number codes. In the card condition, they were also to match the sommelier cards they had filled out with the respective sample. There was no time limit in either phase. The pairs performed both phases together, jointly filling out one sommelier card per target wine in the learning phase; they were also required to give a single joint answer in the recognition phase. The entire procedure outlined above was explained to the participants at the beginning of the experiment, and the instructions were repeated at the beginning of the recognition phase. Joint sessions were recorded using a video camera and voice recorder. After the experiment, the participants completed a questionnaire containing questions pertaining to their demographic information, perceived quality of cooperation, how well they knew their partner, and other issues (the complete questionnaire translated into English is available in **Supplementary Materials**). A more in-depth description of the procedure and the reasoning behind it and other details of the experiment can be found in the original article (Zubek et al., 2016, and its Supplementary Materials).

A total of 123 participants (among them 85 females and one participant who did not state their sex) took part in the experiment. Participants were recruited by advertisements through social media and screened for any conditions that would put them or the quality of the study at risk: contraindications to the consumption of alcohol, smell or taste disorders, professional or advanced knowledge of wines, high frequency of wine consumption, and lack of fluency in the Polish language. Due to the possible effects of advanced age on olfaction (Doty, 1989; Hummel et al., 2007), we also decided to recruit only participants younger than 50 years of age. Altogether, there were 19 pairs with a card[2], 21 without, and 20 solo participants with and 20 without a card. The demographic characteristics of the participants in both conditions are provided in **Table 1**.

In this paper, we present an analysis of the second phase of the experiment (recognition phase) focusing on the dyads. It covers material consisting of 40 videos (one for each dyad), comprising a total of 391 min 15 s of video material. The average duration of a recording is 9 min 46 s, and the median is 8 min 56 s. The shortest recording is 3 min 17 s; the longest is 22 min 41 s.

Data Coding and Analyses

We employed a dual approach to quantify the individual behavior and interaction in each group: manual coding using raters to code the behaviors and automatic coding using software to trace and quantify the movements from the video recordings. We used the ELAN, 2018 (versions 4.9.4 and 5.4, 2016–2018; see also Wittenburg et al., 2006) program to code the timing and type of each relevant behavior. We observed seven main behaviors that constituted vital elements of performing the task: "drinking wine," "smelling wine," "drinking water," "holding cup of water," "holding cup of wine," "marking cup," and "changing cup." Obviously, this selection of coded behaviors does not include all the behavioral categories that could be coded in such a task situation, such as, for example, gaze direction, speech or the participants' interaction with the card. We decided to further focus only on four categories from the ones listed above that were directly associated with performing the task and that recurred frequently enough to allow for discerning patterns: "drinking wine," "drinking water," "smelling wine," and "changing cup."

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[2] One pair with a card was excluded, as in Zubek et al. (2016), because they demonstrated a high level of knowledge about wines.

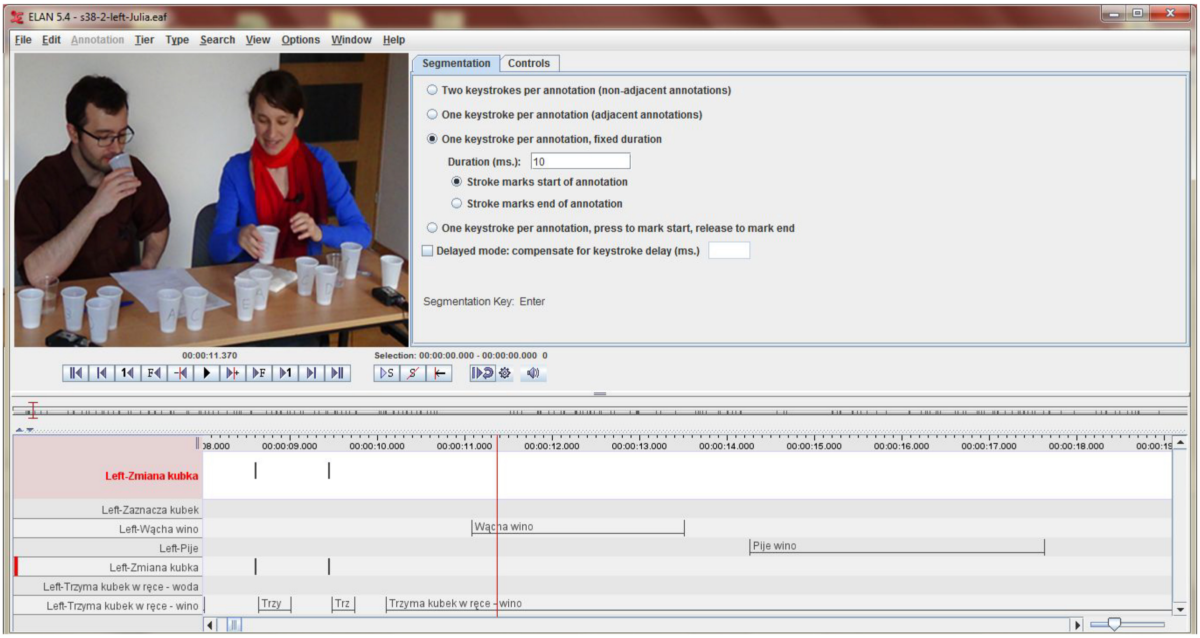
TABLE 1 | Characteristics of the participants in the dyadic condition in the Zubek et al. (2016) study.

	Sex		Dyad composition			Age (years)			Acquaintance level
	Female	**Male**	**Both female**	**Both male**	**Mixed**	**Range**	**Avg.**	**Avg. difference**	**No. of pairs of strangers**
Without card	27	15	10	4	7	18–35	22.2	3.0	12
With card	28	10	11	2	6	18–40	23.0	3.4	15
All dyads	55	25	21	6	13	18–40	22.6	3.2	27

"Avg." means average. Avg. difference pertains to the average difference in age between the members of the dyad. Acquaintance level was indicated on a scale from 1 ("strangers") to 4 ("knows partner very well"). The number of dyads in which at least one person indicated they were unknown to their partner is given in the column "No. of pairs of strangers."

"Drinking wine" was defined as an action of drinking wine from a single cup in a single or prolonged manner, and, similarly, "smelling wine" was smelling – in a short or prolonged manner – from a single cup. In addition to drinking and smelling wine, we also coded such movements as drinking water that is an important part of the professional wine-tasting process. In the case of smelling or drinking, the action began when the cup was held next to the nose or mouth and ended at the first moment in which it was taken away. "Changing cup" was coded when the change of focus occurred "physically" (taking a new cup in hand) or "mentally" (e.g., holding two cups at the same time and changing focus from one to the other or pointing to another cup that was not being held at that moment). All categories were coded as time segments (with a beginning and an end), and only "changing cup" was a point event (as changing focus from one wine to another could occur in several, uncomparable ways, its duration was not taken into account). **Figure 2** shows a screenshot from the coding of the videos in ELAN.

One should note that coding behavioral data involves multiple simplifications. While coding, we discovered the richness of real actions and interactions that could not be captured by our simplified coding schema. We discovered unusual behaviors, such as the action of bending over a cup of wine instead of bringing it to the nose, or actions directed toward the other participant, such as smelling wine from another participant's cup. Another complexity is the ambidextrousness of some actions. A good example of this is the action of smelling two wines at once, using both hands. Even more difficult was defining the level of intentionality in the movements. "Changing cup" was one of the most problematic categories, as the coders had to interpret the participants' behavior and evaluate whether the movement was indeed made intentionally and purposefully. Finally, some of the participants tended to perform semi-professional movements, such as swirling the wine to raise the fragrance. These behaviors require deeper investigation and may be analyzed in further research. Ultimately, repetitive interaction with the raw empirical data



○ Two keystrokes per annotation (non-adjacent annotations)
○ One keystroke per annotation (adjacent annotations)
● One keystroke per annotation, fixed duration
Duration (ms.): 10
● Stroke marks start of annotation
○ Stroke marks end of annotation
○ One keystroke per annotation, press to mark start, release to mark end
☐ Delayed mode: compensate for keystroke delay (ms.)
Segmentation Key: Enter

FIGURE 2 | ELAN screen for coding the timing and categories of behaviors. Written informed consent was obtained from the individuals for the publication of this image.

helped us to improve our coding schema[3] and broaden our understanding of the coding categories and their relation to the videotaped behaviors. A meticulous coding process forces detailed observation, which brings into focus the qualitative aspects of the participants' actions and can be a source of further hypotheses and investigations. In this respect, we were guided not only by the hypotheses we advanced but by a more qualitative exploratory approach.

Behaviors were coded by four coders. A total of 2.5% of the videos were coded by all of the coders to check for coding reliability. The reliability of the coding was assessed using the *Staccato* algorithm – *Segmentation Agreement Calculator according to Thomann* – a tool for evaluating the reliability of video data annotations, designed specifically for evaluating the reliability of gesture annotations (Lücking et al., 2011). The reliability was calculated based on a 10-min 51-s video sample coded by all four coders. We set default algorithm parameters, which include the number of Monte Carlo iterations (1000), nomination length granularity (10), and the level of significance to reject the null hypothesis of chance-based agreement (0.05). The results are given in the form of *the degree of organisation* parameter (which takes values in the interval $[-1, 1]$). The overall average degree of organization for all coding categories was 0.78. For "wine drinking," the overall average degree of organization was 0.96, and for "smells wine," 0.96, which is close to complete consistency (i.e., to maximum value of degree of organization; see Thomann, 2001; Lücking et al., 2011, for detailed description of the method).

The automatic movement extraction and coding consisted of movement quantification analysis performed using the frame-differencing method (Paxton and Dale, 2013). The frame-differencing method codes movement as a change of pixel color. By comparing the values of pixels in two subsequent video frames, the overall movement of an object in that moment can be measured. The method requires the background of the analyzed object to be static and the regions of interest occupied by each participant to be specified. Using our developed PixelTracking software[4], we manually specified two non-overlapping regions of interest and extracted time series describing changes in the movement of each participant. The data were then normalized, and a second-order Butterworth low-pass filter was applied to prevent the false detection of participants' movements caused by fluctuations in light sources (Paxton and Dale, 2013).

These time series were analyzed further using cross-recurrence quantification analysis. Cross-recurrence quantification analysis is a non-linear technique that uses reconstruction of a phase space to analyze the trajectories of two systems (Zbilut et al., 1998). It quantifies the number and duration of occurrences of revisitation of the same state in the state space (given a specified similarity radius) by the analyzed systems, thus providing better insight into their temporal organization and codependency. Applying this method to the data extracted from the video recordings required choosing the following CRQA parameters: radius, delay, and embedding dimension. To this end, we used heuristics implemented in the R package "crqa" (Coco and Dale, 2014) and applied the optimizeParam function to small slices (750 frames) of time series from each session. As a result, the following parameters were chosen: radius = 0.20 (value averaged over all sessions, standard deviation equal to 0.11), delay = 18 (maximum value over all sessions chosen to prevent information loss), and embedding dimension = 2 (the same value was obtained for every session). These parameters were then used to analyze the time series in Commandline Recurrence Plots (Norbert Marwan, ver 1.13, 2006). For each session, the program calculated a cross-recurrence plot that was used to obtain the following measures: determinism, recurrence rate, determinism-recurrence rate ratio, laminarity and the longest vertical line. The statistics were averaged over windows (size – 750, step – 35) along the main diagonal. Additionally, we calculated the absolute amount of movement in a dyad and the difference between the amount of movement of the persons forming a dyad. Thus, each session was characterized by seven movement statistics (see Coco and Dale, 2014, for a detailed description):

- recurrence rate (RR) – how often participants visited similar states, i.e., coordinated movement (probability of recurrence),
- determinism (DET) – how often coordination occurred in prolonged episodes (conditional probability of a prolonged recurrence),
- the ratio between them (DET/RR) – conditional probability of a prolonged recurrence relative to the overall probability of recurrence,
- laminarity (LAM) – how often one system stays for some time in a state visited by the other system (in our case staying in the same state equals to producing movement with constant characteristics),
- longest vertical line (V_max) – the longest episode during which one system has stayed in a state that has been visited by another system,
- the absolute amount of movement in a dyad (abs), and
- the difference between the amount of movement of individuals in a dyad (abs_diff).

Finally, in addition to the complex measures presented above, we made use of the measures from the original study: performance (number of wines correctly identified) and the subjective assessment of the quality of cooperation, self-reported by each participant after the experiment ("How do you assess the quality of the cooperation during the task?") on a scale from 1 ("low") to 7 ("very high") and averaged within each pair.

All raw data used in the analyses (coded behaviors, raw movement signals, and experiment results) are available in **Supplementary Materials**.

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[3] In the initial coding, we decided to add the category of holding the cup with water or wine to investigate if this variable differentiated the examined groups (with and without a card) in some way and if the total contact time with the cup was a variable affecting the performance of the task in any way. We also created the category of marking the cup, which had three subcategories: marking the cup for the first time, changing the previous mark and rejecting the previous mark. However, in the final coding, the category "changing cup" better reflected action organization than "holding cup." "Marking" was a rare event and did not enter this line of analyses.

[4] https://github.com/zubekj/pixel_tracking

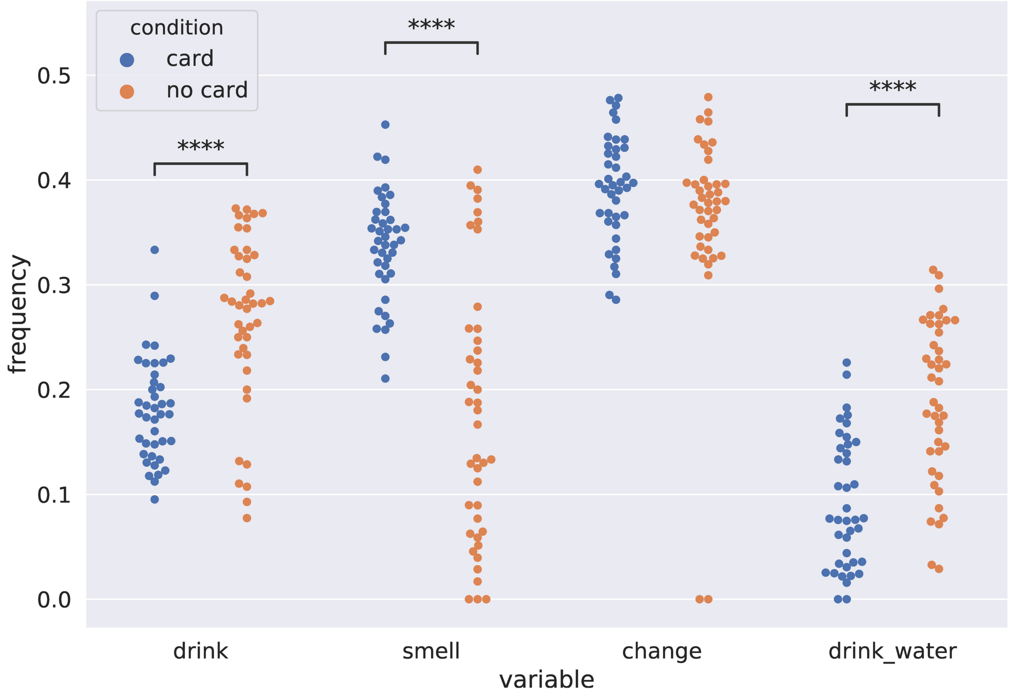

FIGURE 3 | Distributions of event frequencies within the experimental sessions for the two conditions. Each point corresponds to a frequency of a particular event in a single session. Asterisks correspond to significant differences according to Welch's *t* test with the false discovery rate controlled (****$p < 0.001$).

RESULTS

Behavioral Event Frequencies

Using our behavioral coding, we compared the events' frequencies between the two conditions at the level of individual participants. **Figure 3** presents behavior frequencies for the following coded behaviors: "drink" (drinking wine from a single cup), "smell" (smelling a single cup), "change" (picking up a different cup), and "drink_water" (drinking water). To calculate the statistical significance of group differences, we performed four Welch's *t* tests. *p* values were adjusted using the Benjamini–Hochberg procedure (Benjamini and Hochberg, 1995) to control the false discovery rate in the case of multiple testing. Drinking wine occurred more frequently in the "no card" condition ($t = -5.61$, df = 62.72, $p < 0.001$, $p_{adj} < 0.001$), drinking water was more frequent in the "no card" condition ($t = -6.06$, df = 76.45, $p < 0.001$, $p_{adj} < 0.001$), and smelling wine was more frequent in the "card" condition ($t = 5.94$, df = 62.79, $p < 0.001$, $p_{adj} < 0.001$).

Behavioral Event Transition Probabilities

The structure of event sequences was compared in the two conditions. For each session, transitional probabilities were computed, which determined how many events of each type occurred, given the type of preceding event (the event sequences of both participants were used to calculate a single set of transitional probabilities). Repeated occurrences of the same event were excluded (for example, the event sequence "drink"–"drink" was treated as a single occurrence of "drink"). To prevent the counts of events (which – as seen from the previous analysis – were different between the conditions) from impinging on the assessment of differences in transitional probabilities, we calculated mutual information (MI) between consecutive events, which is normalized with respect to the probabilities of single events (Cover and Thomas, 1991; Papapetrou and Kugiumtzis, 2013). MI scores were smaller in the "card" condition than in the "no card" condition (Student's *t* test, $t = -2.46$, df = 39, $p = 0.017$). This means that, contrary to our hypothesis, the sequence is less structured overall in the "card" condition: knowing a previous event provides less information on the next event.

To better understand this result and to detect possible sequence differences between the conditions, we analyzed the transition probabilities for individual event pairs. We calculated the normalized pointwise mutual information score (normalized PMI, **Figure 4**), which is positive when two events co-occur together more often than expected considering their base frequencies, negative when two events co-occur less frequently than expected, and zero if events are independent. Normalized PMI is restricted to the interval $[-1,1]$. There was one session in which the change–smell transition did not occur, and in three sessions, the smell–change transition was not present, which resulted in missing values.

Calculated normalized PMI scores were then compared between conditions (with or without a card) at the level of a session using a series of Student's *t* tests with Benjamini–Hochberg corrections. The results showed several differences between the behavior sequences in dyads working with and without the sommelier card. We established that drinking

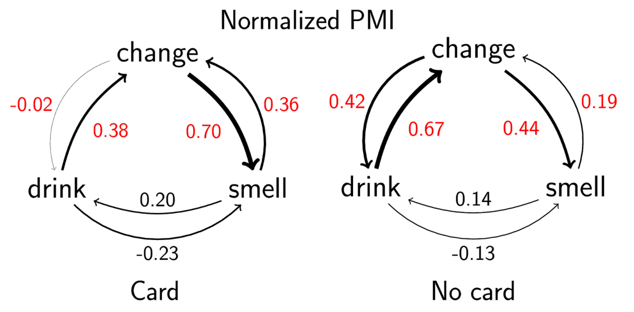

FIGURE 4 | Mean values of normalized pointwise mutual information (PMI) scores for event transitions in the two conditions. Values significantly different between conditions are printed in red.

immediately after the cup change was less prominent among pairs with the card ($t = -5.66$, df = 38, $p < 0.001$, $p_{\text{adj}} < 0.001$), while smelling after a cup change was more prominent ($t = 4.85$, df = 37, $p < 0.001$, $p_{\text{adj}} < 0.001$). There were also differences regarding the events preceding a cup change: drinking was less prominent ($t = -5.40$, df = 38, $p < 0.001$, $p_{\text{adj}} < 0.001$) and smelling was more prominent ($t = 2.27$, df = 35, $p = 0.030$, $p_{\text{adj}} = 0.045$) in pairs working with the card. Consequently, while pairs without the card had a similar tendency to start an interaction with a new wine by drinking or smelling it, pairs with the card favored smelling. Similarly, pairs without the card ended their interaction with a wine more often by drinking, but among pairs with the card, drinking and smelling were equally prominent. Generally, we may conclude that introducing the sommelier card opened up new possibilities for interacting with the wine via the olfactory modality, even when the base frequencies of events were accounted for.

Behavioral Coordination Within Pairs

We demonstrated that the presence of the sommelier card significantly altered the behavior of individuals. According to our hypotheses, it should also influence the coordination between participants working together. As a first step, we compared behavior frequencies within pairs. For each pair, we calculated the absolute difference between the observed frequencies of a particular behavior between the two participants. The differences were small (mean difference 0.029, max 0.136), and no significant differences between the "card" and "no card" groups, according to Welch's t test, were observed (the statistics for specific events were as follows: drink – $t = -0.51$, df = 38.74, $p = 0.612$, smell – $t = -0.64$, df = 38.95, $p = 0.523$, change – $t = -0.23$, df = 38.67, $p = 0.821$, drink_water – $t = -0.07$, df = 37.54, $p = 0.945$).

To gauge patterns of behavioral coordination between the two participants within pairs, we discretized time in our sequence of behaviors and obtained standardized time series with a sampling frequency of 0.5 s. For a specified time lag l, we calculated probability $p(\mathrm{A}_t, \mathrm{B}_{t+l})$ that if participant A performs an action at time t, participant B performs the same action at time $t + l$. Positive lag corresponds to participant A leading and B following, and negative lag to the opposite scenario. The obtained probabilities were normalized by dividing them by the baseline value (the probability of the two events occurring in this configuration at random) to obtain co-occurrence ratio $r = p(\mathrm{A}_t, \mathrm{B}_{t+l})/p(\mathrm{A}_t)/p(\mathrm{B}_{t+l})$. The co-occurrence ratio was defined only when the considered event occurred at least 10 times for each participant. We focused our analysis on lags ranging from −25 steps to 25 steps (−12.5 s to 12.5 s), because maximal values of the co-occurrence ratio were observed in this time window. The characteristics of each profile were further aggregated into two values: the mean observed co-occurrence ratio within the profile for lags [-25,25] (**Figure 5**) and the normalized difference between the left and right sides of the central profile ($d = |L-R| / (L + R)$, where L is the sum of ratios for lags [−25,0) and R is the sum of ratios for lags (0, 25]). The mean co-occurrence ratio might be interpreted as the mean amount of structured coordination observed for the pair. Left–right (LR) difference describes the amount of asymmetry in the roles in the interaction: a larger LR difference means that one participant consistently leads and the other follows. These two measures calculated for each pair separately were used in further analyses. **Figure 6** presents the coordination statistics for different behaviors.

Because of the irregular shape of the distributions, the significance of these results was calculated using the Mann–Whitney U test to compare the distributions of the maximum ratio and LR difference between the two groups. The false discovery rate was controlled using the Benjamini–Hochberg correction. When drinking wine, pairs with a card displayed a greater amount of role asymmetry, as shown by the LR difference ($U = 330.0$, $p = 0.002$, $p_{\text{adj}} = 0.016$), and a trend toward stronger coordination below the level of significance ($U = 290.0$, $p = 0.038$, $p_{\text{adj}} = 0.101$). For drinking water, we observed a trend toward greater coordination in the group with the card ($U = 190.0$, $p = 0.017$, $p_{\text{adj}} = 0.068$), although the effect did not reach statistical significance after adjusting for multiple comparisons. These results indicate that in the "card" condition, participants were coordinated in a particular way when drinking, and stable leader–follower roles emerged. Neither of these characteristics of the pairs correlated with task performance or reported satisfaction with the collaboration (F test for the linear model predicting task performance based on behavioral coordination statistics: $F = 0.81$, df = 4;34, $p = 0.525$, F test for the linear model predicting satisfaction based on behavioral coordination statistics: $F = 0.52$, df = 4;34, $p = 0.718$).

Low-Level Movement Coordination

We were also interested in how card-dependent patterns of behavior, which were quantified via the behavioral coding, translate into differences in the low-level movement properties of the interacting dyads, obtained from the frame-difference method and cRQA analysis.

To confirm that the obtained cRQA statistics are non-trivial and capture real variability in behavior, we analyzed the data using a pseudosynchrony paradigm (Bernieri et al., 1988). Time series describing the total movement of one subject from each session were paired with the movements of a person from a different session, thus allowing us to compare the results with a baseline obtained from randomly assigned pairs. This baseline allowed us to distinguish between

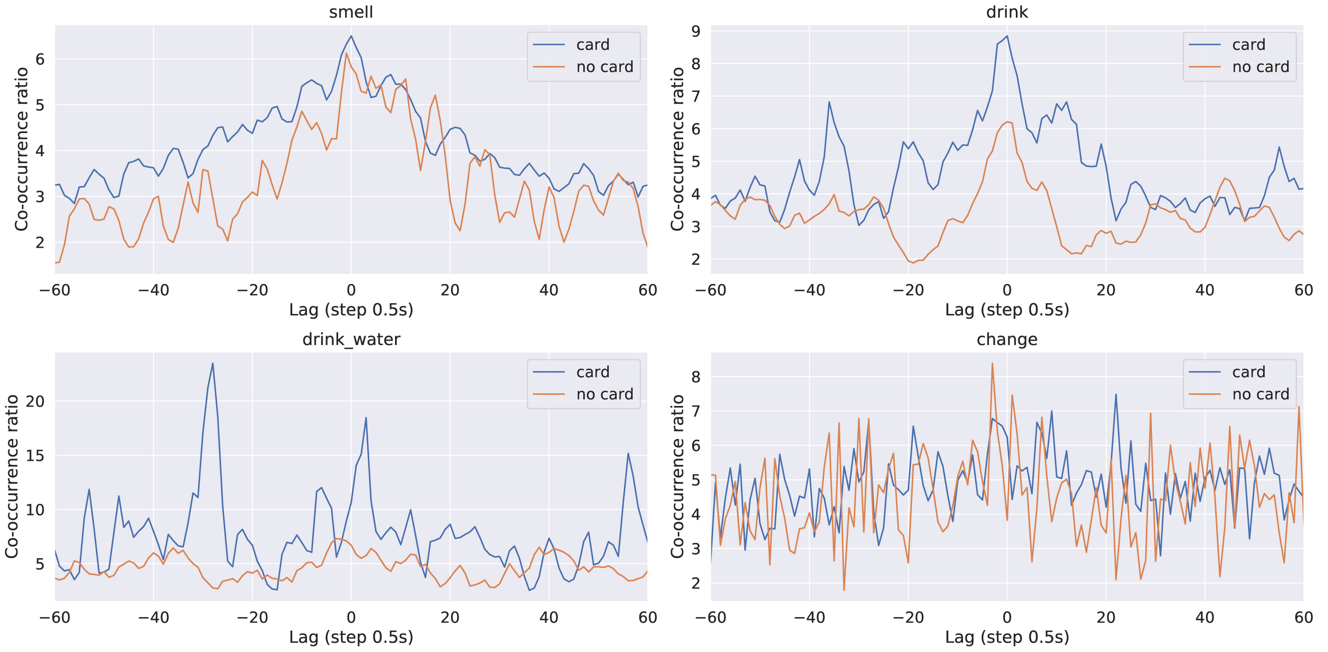

FIGURE 5 | Observed coordination structures for different events in the two groups for the four coded behaviors. Averaged time-lagged profiles of the co-occurrence ratio are presented for each event separately.

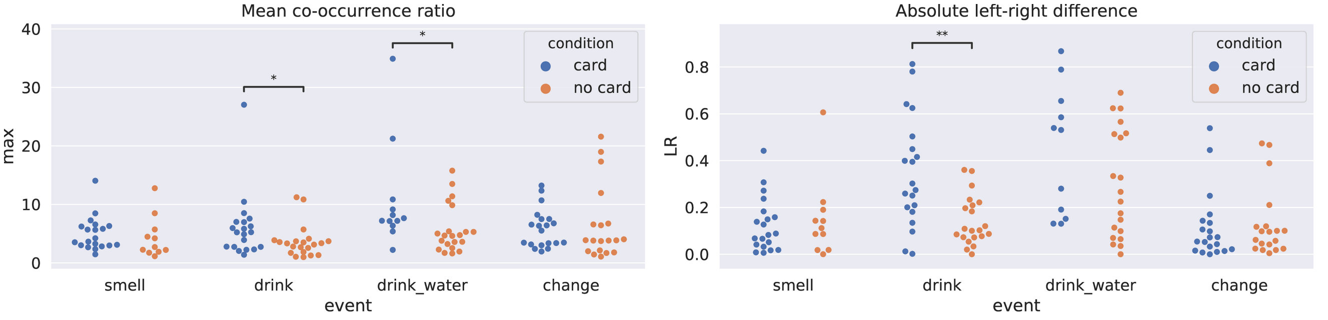

FIGURE 6 | Distributions of the maximal co-occurrence ratio observed (for any lag) and the absolute difference between the left and right side of the profile. Values are calculated separately for each event category. Significant differences between the two groups according to the Mann–Whitney *U* test are marked with asterisks (*$p < 0.05$, **$p < 0.01$).

false coordination arising from the task structure (for example, the natural sequence of wine tasting followed in every session) and true interpersonal coordination. We compared the values of the cRQA measures between 40 real pairs and 40 generated artificial pairs using the Welch *t* test (the false discovery rate was controlled using the Benjamini–Hochberg correction). The results are given in **Table 2**. For three statistics (RR, DET, and DET/RR), we found significant differences; the other two (V_max and LAM) did not reach significance. Overall, cRQA statistics are able to capture the difference between the coordination of real pairs and that of artificial pairs.

As a next step, we compared the overall movement coordination statistics between the "card" and "no card" conditions. We used logistic regression to determine whether the movement characteristics allow for prediction of the condition in which the task was performed (with or without a card).[5] All of the cRQA measures mentioned before were used as predictors: determinism (DET), recurrence rate (RR), the ratio between them (DET/RR), laminarity (LAM), and longest vertical line (V_max), as well as the absolute amount of movement in a dyad (abs), the difference between the amount of movement of individuals in a dyad (abs_diff) and reported satisfaction with cooperation. The model was compared with a null model using the likelihood ratio test, and the outcome was not significant (model log-likelihood

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[5] Note that it is the experimental condition that affects movement coordination and not the other way around, so this is a case of anticausal modeling. We use logistic regression as a multivariate analog of simple correlation, where the direction of the relation is not specified.

TABLE 2 | Welch *t* test results for the comparison of cRQA statistics between real and artificial pairs (pseudosynchrony).

cRQA measure	*t*	df	*p*	p_{adj}
Recurrence rate (RR)	3.47	46.47	0.001	0.005
Determinism (DET)	2.99	73.24	0.004	0.010
Determinism to recurrence rate ratio (DET/RR)	−2.39	77.18	0.019	0.031
Longest vertical line (V_max)	1.42	72.20	0.160	0.160
Laminarity (LAM)	1.58	77.20	0.118	0.148

TABLE 3 | Coefficients of the linear model predicting participants' satisfaction in the group with the card.

	Standardized coefficient	SE	*t*	*p*
(Intercept)	−0.32	0.12	−2.65	0.023*
RR	−0.22	0.29	−0.75	0.467
DET	−0.90	0.47	−1.94	0.078
DET/RR	−0.48	0.28	−1.72	0.114
LAM	0.42	0.36	1.19	0.260
V_max	0.47	0.31	1.51	0.159
abs	−1.08	0.22	−4.90	< 0.001***
abs_diff	1.16	0.23	5.00	< 0.001***

*The results of the Wald test for the significance of individual variables are reported (degrees of freedom of t statistic df = 11). Significance levels are marked with asterisks: *p < 0.05, ***p < 0.001.*

TABLE 4 | Coefficients of the linear model predicting task performance in the group with the card.

	Standardized coefficient	SE	*t*	*p*
(Intercept)	0.53	0.36	1.49	0.167
RR	−2.00	0.70	−2.89	0.016*
DET	1.34	1.26	1.06	0.313
DET/RR	1.33	0.74	1.67	0.125
LAM	−1.05	0.89	−1.19	0.262
V_max	2.61	0.80	3.27	0.008***
Satisfaction	0.37	0.70	0.52	0.615
abs	−1.46	0.92	−1.58	0.145
abs_diff	0.75	0.98	0.76	0.462

*The results of the Wald test for the significance of individual variables are reported (degrees of freedom of t statistic df = 10). Significance levels are marked with asterisks: *p < 0.05, ***p < 0.001.*

LL = −27.68, $\chi^2 = 11.859$, df = 8, $p = 0.158$), thus not supporting such a prediction.

We also determined whether the relations between movement coordination and two other variables, task performance and reported satisfaction with collaboration, depend on the presence of the sommelier card. For each dependent variable, two separate linear regression models were created: one for the group with the card and one for the group without the card. We tested overall model significance using *F* tests. The relationship between movement characteristics and reported satisfaction was significant in the group working with the card ($F = 5.631$, df = 7;11, $p = 0.006$) and not significant in the group without the card ($F = 0.953$, df = 7;13, $p = 0.502$). **Table 3** reports the regression coefficients for the significant model in the "card" group. We can see that the most important predictors were abs, abs_diff, and DET (though the last one did not reach significance). This means that participants reported greater satisfaction with the interactions (a) that contained less overall movement (abs), (b) in which clear roles were established (one person moving more than the other; abs_diff) and (c) in which synchronization episodes were not too long (DET). A similar analysis was performed for the relation between movement characteristics and performance (participants' satisfaction was included as an additional variable). The model was also significant in the group with the card ($F = 3.23$, df = 8;10, $p = 0.043$) and not in the group without the card ($F = 0.71$, df = 8;12, $p = 0.681$). We report the coefficients of the significant model in the group with the card in **Table 4**. Significant variables included the recurrence rate and the longest vertical line. This translates to lower synchronization between participants (RR) and higher overall stability (V_max).

Clearly, movement coordination alone does not allow us to distinguish between pairs with the card and pairs without the card and allows us to predict task-related variables only in dyads with the card. This means that introducing the sommelier card does not visibly alter movement coordination but does change the way that coordination impacts interaction outcomes.

DISCUSSION

The results of our study revealed systematic differences between the pairs using the sommelier card and those who conversed freely without any aid. This cultural artifact can be said to impinge at the individual and systemic levels, influencing (I) the organization of individual behavior, both in the frequency distributions of particular events and in their sequential organization, (II) the coordination of partners on the level of actions performed, and (III) the relation between movement coordination within dyads and the outcome variables of the experiment (the overall performance and satisfaction with the interaction).

(I) At the individual level, participants using the sommelier card employed the olfactory modality more extensively: wine smelling occurred more frequently than in the "no card" condition, whereas wine drinking occurred less frequently. Contrary to what was expected, the overall predictability of behaviors in a sequence did not increase when people were using the card; thus, we cannot interpret the card as a simple constraint that reduces the degrees of freedom of the system. The card does, however, make some transitions between behaviors more frequent than others (controlling for the increased frequency of "smell"). It makes participants less likely to start an interaction with a sample of wine by drinking it than participants without the card and more likely to start an interaction by smelling the wine. The card seems to also make it more probable that the wine will be changed after only being smelled, indicating that participants may prefer to first compare the wines in a single modality (smell) before passing to another modality (taste).

These results can be interpreted as the influence of the professional tool, which codifies not only vocabulary but also the procedure for tasting, describing, and recognizing wines. The card suggests to participants a specific order of behaviors related to wine tasting. However, we found that sequences of behaviors had lower mutual information in the "card" than in the "no card" condition, thus appearing to be less structured. This result was surprising and has verified the way to think about constraints in this situation. We thought (initial hypothesis) that spontaneous tasting would be less structured than tasting with the card. But the card made more frequent the very behavior (smelling) that was underrepresented in the group without the card. Thus, on the level of general entropy – due to encouraging new possibility – we have more equal distribution over the states. This shows that a simple inference from general entropy to behavioral structure complexity might be misleading. In this context we can conclude that the card does not constrain but rather creates new possibilities for participants. These possibilities are akin to the wine tasting strategies employed by professional sommeliers; thus, the sommelier card successfully transferred the embodied behavioral knowledge of wine drinking culture to the naive participants.

(II) At the collective level, we observed a certain degree of coordination of behaviors in both conditions. When drinking wine, pairs with the card displayed a greater amount of role asymmetry than pairs without the card. One of the aspects of asymmetry might be a tendency to establish a leader–follower relation. Participants following the guidelines given by the card drank their wines in a measured and deliberate fashion, focusing also on coordinating their behavior with that of their partner. Thus, we may conclude that the card changes not only the individual behaviors of the participants but also the relation between them.

Such structuring of the interaction, establishing roles and distributing the workload, can be considered a form of adaptation to the demands of joint-action tasks (Marsh et al., 2009; Knoblich et al., 2011; Dale et al., 2013). Indeed, in the original study by Zubek et al. (2016), pairs with the card tended to perform with decreased variance error. The role of the card as a modifier of relations is also consistent with the results of the original study, which found that the presence of the card modified the wine recognition performance of pairs only and not of participants tasting wines individually. Curiously, the observed differences in coordination concern only drinking and not smelling. This might be connected to culturally embodied practices concerning wine tasting that are familiar to the participants. There is a widespread custom of synchronous drinking – making a toast – on various occasions, while no equivalent practice exists for smelling. Additionally, among some pairs without the card, smelling behaviors were so rare at the individual level that it was impossible to measure their coordination in a meaningful way.

(III) Finally, no significant differences between conditions were found concerning low-level movement coordination, but it occurred, that the card acted as a moderator altering relations between movement coordination and two other variables: task performance and reported satisfaction with the collaboration. It can therefore be said that even if the amount of movement is not specific to the system as a whole, the characteristics of the movement gain some functional meaning in the presence of the artifact. The content of participants' interactions in the two groups was qualitatively different, as the proportions of smelling and drinking changed, but those changes were not apparent in the low-level movement analysis. Among pairs with the card, satisfaction with the collaboration was negatively associated with the overall amount of movement and positively associated with the asymmetry in the activity of the participants, while task performance was negatively associated with the overall amount of coordination and positively associated with the presence of long episodes of repeated movement. These results strengthen our claim regarding the importance of structure and established roles. While raw movement synchrony is reported to be positively correlated with affiliation (Hove and Risen, 2009), Abney et al. (2015) demonstrated that it is weaker coupling (less synchrony) that predicts performance in a structured task involving the manipulation of physical objects and suggested that role asymmetry may also be beneficial in such tasks. This may explain why we observed significant effects of movement coordination only among pairs with the card, as this condition imposed more structure and required the sharing of physical items (cards) between participants.

Summarizing and attempting to generalize, we could say that in terms of degrees of freedom, the sommelier card increased the number of degrees of freedom at the individual level (introducing new behaviors) and constrained degrees of freedom at the collective level (structuring coordination). Recall that in the original study (Zubek et al., 2016), pairs with the card were characterized by smaller variance in their answers and more concise vocabulary in their linguistic interactions. These are all facets of the same tendency of the reduction of degrees of freedom at the collective level. The observation that, at the individual level, degrees of freedom seem to increase explains why in the original study the sommelier card did not reduce the variance of answers in the individual conditions.

We stress that this complex picture in which the presence of a sommelier card opens some possibilities while restricting others should be seen as natural for social and cultural phenomena studied in ecological settings. Complex systems by definition cannot be reduced to simple unidirectional, linear relations. Our findings – clarifying the results of the previous study – were made possible by the choice to look for structured behavior on multiple different levels using different operationalizations.

CONCLUSION

Radically embodied perspectives on the development of skills and expertise underscore the role of the acting body in a structured environment. Both the formation of the body through repetitive practice and the progressive modification of the environment are crucial for ratcheting the effects of learning, which is understood as embodied "enskillment" (Ingold, 2000). While the former acts on the developmental and learning time scales, the latter concerns the cultural accrual of expertise.

To understand how the modification of the niche aids in the preservation and propagation of skills, an important task would be to study how this niche, including artifacts, impinges on and controls the embodied practice. This was the main aim of this research: to determine how a culturally created tool for wine description and recognition changes the actual individual practice of such tasks and the coordination of this practice in collective settings. We believe that designing strategies to study such influences in a more systemic way, taking into account their situated and embodied aspects, is an urgent task given the plethora of increasingly technologically advanced artifacts that transform our daily practice and interactions, often in an irreversible way.

In our research, we sought to integrate the sociological, anthropological, and psychological perspectives. The former allowed us to treat artifacts in more active and agentive ways than psychology traditionally permits. Artifacts have the power to change the practice of individuals and create novel relations among them, because they are elements of distributed cognitive systems carrying the intentionality of their makers. In building this integratory framework, we drew on ecological psychology as conceptually helpful to account for the shaping of artifacts as part of the cognitive niche and, in turn, for their role in promoting certain behaviors as individual and interactive affordances within social events. This interdisciplinary approach also facilitates the integration of qualitative and quantitative methods from anthropology, psychology, and the dynamical systems approach in an attempt to first identify the crucial factors and behaviors and then to operationalize the expected effects in a measurable way.

The results of this research testify to the utility of both qualitative analysis and dynamical systems methods, in which the analysis of degrees of freedom on various levels and the examination of systemic stability, variability, and complexity allowed a comprehensive picture of the artifacts' role to be formed. The sommelier card opened some possibilities at the individual level, bringing into focus modalities and behavioral organizations more in line with professional practice, but also seemed to constrain the collaboration by creating new relations between participants. However, we are aware that both this research tackling the specific problem of wine tasting as embodied practice and the general problem of how to study embodied and situated learning in all its complexity require much further work.

The next concrete step would be to compare the novices in our study to professionals to see if the changes are indeed toward the more skilled practice. The coordinative role of the card may also differ in the professional pairs. Qualitative research on the phases of the task could provide more insight into the ability of the artifact to create specific relations. An important lesson from this study that we hope will continue to inform our research is the conviction that focusing on a single level would not allow us to appreciate the complexity of the studied phenomena. Individuals co-create collective systems in an embodied practice and this can be studied at several levels of organization and using multiple types of observables, from coded behaviors and their frequency and timing, to task performance and assessments of satisfaction with the interaction, to automatic movement analyses. In such an embodied and systemic view, cultural artifacts are considered to have some kind of agency, changing the behaviors of other actors and the relations among them, co-creating social reality.

On a more methodological, final note, the next steps addressing the development of methods to study skill acquisition within the embodied situated and distributed perspectives will involve conceptual work on how to integrate the methods and domains within an explanatory pluralist approach (Abney et al., 2014) in which different scientific disciplines lend their insights and methods to understand the studied phenomena on different scales and at different levels of organization.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Polish Academy of Sciences Ethics Committee, Institute of Psychology. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

JR-L, JZ, and MD designed the study. JK and NK coded the data. JZ, MD, and KZ performed the behavioral analyses. MK performed the movement analyses. JR-L, JK, NK, KZ, MD, MK, and JZ wrote the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2019.02671/full#supplementary-material

DATA SHEET S1 | Sommelier Card (original and translation).

DATA SHEET S2 | Participants' Questionnaire (original and translation).

DATA SHEET S3 | Raw data files (descriptions in README.txt files).

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Flow as an Embodied State. Informed Awareness of Slackline Walking

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Flow during exercise has been theorized and studied solely through subjective-retrospective methods as a "scull bound" construct. Recent advances of the radical embodied perspectives on conscious mind and cognition pose challenges to such understanding, particularly because flow during exercise is associated with properties of performer's movement behavior. In this paper we use the concept of informed awareness to reconceptualize flow experience as a property of the performer-environment coupling, and study it during a slackline walking task. To empirically check the possible relatedness of the behavior-experience complementary pair, two measures were considered. The experiential realm was quantified by the flow short scale and the behavioral realm by the Hurst (H) exponent obtained through accelerometry time series of the legs and the center of body mass (CoM). In order to obtain a coarse-grained insight about the degree of co-varying within the perception-action flow of performers, we conducted correlational and multiple regression analyses. Measures of behavioral variables (H exponents of the dominant, subdominant leg and the CoM, were treated as explanatory, and the flow scale and its subscale (fluency of movements and absorption) scores asresponse variables containing summarized information about perceptual experiences of performers. In order to check for possible mediating or confounding effects of training parameters on the action-perception variables' covariance, we included two additional variables which measured the degree of engagement of participants with the task. Results revealed that the temporal structure of fluctuations of the dominant leg, as measured by the Hurst exponent, was a strong mediator of effects of training variables and the subdominant leg fluctuations, on the flow scale and the subscale scores. The magnitude of Hurst exponents of both legs was informative about the degree of stability within the performer-environment system. The degree of critical slowing down, as measured by Hurst exponents, consistently co-varied with the flow scale and subscales. The experience of flow during the slackline walking task was dominantly saturated by the perceived fluency of movements and less so by the absorption experience. The stable co-variance of perception-action variables signified the embodied nature of the flow experience.

Keywords: radical embodiment, informed awareness, ecological dynamics, skill, stability, slackline

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INTRODUCTION

Flow has been historically investigated in sport and exercise for its association with exceptional performance (Jackson et al., 2001; Swann et al., 2018). Commonly defined as a harmonious psychological state, intrinsically rewarding, involving intense focus and absorption in a specific activity (Csikszentmihalyi, 1975, 2002; Swann et al., 2018; Stoll, 2019), flow has been contextualized in a framework of challenge-skill balance, clear goals and sense of control (Jackson and Csikszentmihalyi, 1999; Nakamura and Csikszentmihalyi, 2002). Under this view, the state of flow has been traditionally measured solely by subjective methods (Jackson and Eklund, 2002, 2004) without attempts to relate it *empirically* to behavioral measures. This is curious because in physical activities the state of flow was theoretically connected to the fluency of movements (Rheinberg et al., 2003; Engeser and Rheinberg, 2008), which obviously has a behavioral, action content. In this paper we make the first empirical attempt to reconcile this methodological and theoretical gap.

Optimal psychological experiences, underlying the excellence in performance, have been mainly related to flow or clutch states, typically experienced in contexts of achievement and pressure (Swann et al., 2017a,b). In contrast, flow has been generally described in contexts of exploration and flexible outcomes as well as experiences of enjoyment during the activity and lower perceived effort (Swann et al., 2019). As such, the relationship of flow with performance in exercise has been widely reported in the literature (Dietrich, 2004; Engeser and Rheinberg, 2008; Schüler and Brunner, 2009; Fernández et al., 2015; Ufer, 2017). In this line, the basis of flow has been mostly settled on psychological (Swann et al., 2017a,b; Stoll, 2019), physiological (Dietrich, 2004; Keller et al., 2011; Tozman et al., 2015) and psychophysiological factors (Swann et al., 2012). This research has found evidences of brain inhibition of self-reflective introspection during tasks, self-awareness reduction, focused attention and automatic actions among other effects (Jackson and Csikszentmihalyi, 1999; Nakamura and Csikszentmihalyi, 2002; Goldberg et al., 2006; Harris et al., 2017). Flow state has been also described through sensations like lack of weight, lack of fatigue, movement efficiency, and more integratively, as fusion with the environment (Fuentes-Kahal and del Cerro, 2012; Bertollo et al., 2016). In this line, the ecological psychology, and more concretely the ecological dynamics, explains the conscious mind as the very physical relation which emerges at the level of performer-environment system (Araújo et al., 2017). Consequently, phenomenological experiences cannot be understood simply embracing an organism-centered view (Davids and Araújo, 2010).

Within the framework of ecological dynamics, the performer and the environment are continuously integrated as the action regulation unfolds. As the perceptions of affordances (opportunities of action) contingently regulate the actions, and hence cognitions, actions reciprocally create new perceptions for prospective (future) actions. This action-perception cycle is crucial for understanding how conscious experiences emerge. The *informed awareness* is the information about oneself (e.g., proprioception, interoception) *in relation* to the environmental information (Shaw and Kinsella-Shaw, 2007). In this paper, we assume that it is this informed awareness that can reach the state of flow. According to the flow short scale (FSS) (Rheinberg and Vollmeyer, 2003; Rheinberg et al., 2003; Engeser and Rheinberg, 2008; Peifer et al., 2014), we approach the flow experience as consisting of two dimensions: (a) fluency of movements, i.e., sense of control, and (b) state of absorption by the activity when demands of tasks and skills are in balance (Sheldon et al., 2015). The informed awareness in the state of flow hence would incorporate the self-information of fluent and flexible control of the body-environment coupling and dominantly task goal focused attention. The state of *non-flow* would then be experienced as non-fluent, non-flexible and hence effortful control of the body-environment coupling with dominantly internal focus of attention.

Several types of specifying information are constitutive of the informed awareness (Shaw and Kinsella-Shaw, 2007), such as: information of performer's needs, goals, effective means, the adaptiveness of enacting those means, as well as the progress toward the goal. These types of information are dynamically assembled in a form of a cycle consisting of continuous perception of and acting on affordances which have been defined as opportunities, invitations or solicitations for action (Gibson, 1979; Araújo et al., 2006; Withagen et al., 2012; Bruineberg and Rietveld, 2014), dwelling on many time scales. Every bodily action (performatory or exploratory) has a perceptual, and hence cognitive, role. Cognition is being constrained on-line by actions, and in this sense, bodily actions as well as the environment are constitutive to the cognition itself. In other words, informed awareness, as well as cognition as a part of it, is a distributed, embodied and thus, emergent property (Balagué et al., 2019) of the performer-environment system. In challenging[1], non-trivial tasks, demanding high skillfulness, the larger the adaptiveness of dynamic assembling of these types of information (i.e., attunement to affordances), the higher the flow is. The adaptiveness of the dynamic assembling would *behaviorally* correspond to the *fluency of movements*, which is one of the two subscales of the FSS. This means that the fluency of movements is a necesary (but possibly not sufficient) for the experience of flow. Hence, within the ecological dynamics framework the fluency of movements as important component of flow can be defined as a locally[2] optimal attunement (Bruineberg and Rietveld, 2014) to and acting on affordances during challenging tasks. That is, the behaviorally manifested fluency of movements would be a consequence of the attunement to the affordances. Consequently, the *subjective experience* of fluency of movements (sense of control), as a component of the informed awareness, would be a consequence of the attunement to affordances. This attunement to affordances would also stimulate the absorption component of the flow

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[1] Degree of challenge can be defined as a relation between the nominal task difficulty and the skill level of the performer.

[2] Locally optimal – here means that there exist performer-environment configurations which temporarily and contingently enable the maximally possible fluency of perception – action cycle of the performer. This statement does not entail existence of mental representation with content in a form of e.g., pre-set optimal movement execution sequence.

experience by maintaining a task goal instead of internally proprioceptive focused attention due to the effortful control.

As the informed awareness is a conscious experience, it follows that it is reportable, i.e., subject to verbal reports. This means that although informed awareness, *itself*, is not a process involving propositional content, it can be nevertheless socio-linguistically contextualized (by experimenters who linguistically engage participants) in such a way so that the performer can provide verbal reports[3]*about* it. Hence, the data collected using the flow questionnaire can be defined as: judgment based time-delayed, coarse-grained verbal reports about the informed awareness experienced by performers during their engagement with the task. We use the word "coarse-grained" because while the informed awareness fluctuates at different time scales, the verbal reports must summarize that rich experience in a form of verbal statements. While the results of such questionnaires cannot be treated as a "gold standard" in determining behavioral or phenomenal experiential processes, it is also true that the concept of flow experience was and is still operationalized only in a form of questionnaire. In reaction to it, current literature is suggesting to offer more practical setting in collecting real-time data and capturing the dynamic nature of flow in exercise (Jackman et al., 2019).

Then, of particular interest for our purposes was considering a task emerging from a strong performer-environment coupling, in which the actions of the performer change the state of the environment and vice versa, and which co-regulating cycle exists at more than one characteristic timescale. Slackline walking is one of such challenging tasks which, besides the important visual coupling, relies on the tight mechanical coupling of the performer with the slackline (Paoletti and Mahadevan, 2012). The goal of the task is to keep balancing the body in upward position on the slackline positioned at some height from the ground, and walk successfully some distance. Dynamically, it is an unstable inverted pendulum system with extremely narrow support base, which has to be stabilized by continuous perceptions-action cycles. This process of stabilization of an unstable system generates fluctuations. The body-slackline coupling is so strong that the fluctuations of the contact feet (body) are kinematically indistinguishable from the fluctuations of the slackline (environment) itself. However, if the slackline has, for example, different tension these fluctuations will change their character and the rest of the cognitive engagement will have to change as well. The cognitive engagement of the performer extends out of the body including the environment. Hence, kinematic fluctuations are in fact fluctuations of the whole performer-environment system rather than merely fluctuations of the performer or environment alone (**Figure 1**). This mechanical contact deforms the feet tissues and provides tactile and proprioceptive information for the state of coupling between the performer and the environment. The specifying haptic information enables the feeling of the limb positions and their changes relative to each other, relative to the body, and relative to the environment. The deformation of feet tissues, as well as other bodily components and their immediate response, due to their elastic-mechanic properties is the first level of movement and posture control. This control involves the body as direct regulator (inhibitor or activator) of the rest of relevant cognitive engagements in accomplishing the task. In this sense the cognition is embodied (Van de Laar and Regt, 2009). The task requires a continuous perceptual coupling of the performer with the slackline, and the rest of the environment, in order to trace minute changes in slackline-body fluctuations. This is necessary in order to avoid the enhancement of fluctuations through a positive feedback which would inevitably bring about a loss of stability of the center of mass (CoM) and task disengagement. In other words, performers continuously strive to stabilize the perception of walk-on-ability affordance by continuous adaptation of their body movements and perceptual systems at different time scales. Any deviation from this locally optimal attunement to the walk-ability affordance induces a tension that has to be reduced by additional action. This tension reduction is equivalent to stabilizing their CoM. As the slackline-body coupling shapes the external – and self-information by continuously regulating the actions of performer, the coupled body-slackline dynamics becomes constitutive of the informed awareness. The adaptiveness of this dynamic information assembling is reflected in fluency of movements of limbs and the CoM of the body. In other words, the smaller and smoother the deviations from the locally optimal attunement and needs of their reduction, the higher the flow experience of performers would be. In this sense, flow experience as constituent of the informed awareness arises and is maintained through the shared information (defined as co-varying processes) within the locally optimal perception-action cycles of performers. In other words, the complementary pair of flow experience and behavior may be formulated as a dynamic product of these co-varying processes that create the locally optimal perception-action cycles. Verbal reports are just propositions about these co-varying processes constituent of the informed awareness.

Previous research has shown that stability during standing posture and human locomotion in unsteady conditions is produced through adjustments of motor control strategies' timing and compensatory synergies (Wang et al., 2014; Santuz et al., 2018). Particularly important study in this sense is Delignières et al. (2011) which convincingly argued about the velocity (and not position) dependent control of postural sway. These compensatory movements produce kinematic fluctuations around the task goal value, i.e., maintaining orthogonal (90°) and collinear to gravity force vector position of body with respect to the slackline support base, and maybe detected and classified according their stabilizing or destabilizing effects. Quickly suppressed deviations would tend to provide a better stabilizing control; in contrast, fluctuations that would positively add to the already extant deviation would tend, especially on longer time scales, to produce larger deviations from the task goal and a destabilizing effect. The temporal co-variation among the subsequent adjustments must be negative and produce

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[3] Although uncommon, verbal reports have been used in ecological psychology. For example, the classical work of Warren (1984) used verbally reported judgments about affordances, i.e., informed awareness, in a stair-climbing task.

FIGURE 1 | Slacklining with accelerometers placed in both ankles and the Center of Mass. Written informed consent was obtained from the depicted individuals for the publication of these images.

anti-persistent or anti-correlated time variability. Otherwise, positively correlated adjustments or persistent properties would generate larger fluctuations from the task goal. That is, in anti-persistent fluctuations, deviations in one direction are statistically more likely followed by subsequent deviations in the opposite direction, and in persistent fluctuations deviations in one direction are statistically more likely to be followed by subsequent deviations in the same direction. Persistent fluctuations, signifying critical slowing down phenomenon and the impending instability (Scheffer et al., 2009), have been found in more rigid control during exercise, e.g., cases of extreme fatigue (Vázquez et al., 2016). On the other hand, anti-persistent fluctuations have been related to tighter, but rapid and flexible, control of kinematic variables (Terrier and Dériaz, 2012; Vázquez et al., 2016). Velocity-based control (with a transition from anti-persistence to persistence) have been shown in control of the postural sway (Boulet et al., 2010; Delignières et al., 2011). Moreover, some researchers have found relationships between experience, training, and skill levels with temporal co-variation of performance variables (Wijnants et al., 2009; Den Hartigh et al., 2015; Nourrit-Lucas et al., 2015). In particular, the postural and stride to stride control has been studied using the temporal variability of kinematic variables and quantified through Hurst (H) exponents (Balasubramaniam et al., 2000; Boulet et al., 2010; Delignières et al., 2011; Terrier and Dériaz, 2012; Vázquez et al., 2016).

Accordingly, based on what was discussed above, the aim of the current study was to capture the effects of the co-varying bi-directional process within the continuous perception-action cycle of a slackline walking task. Particularly, we were interested on how the dynamical stability of performance affects the embodied and extended information that shapes the flow experience in performers.

MATERIALS AND METHODS

Participants

Nineteen volunteer Spanish slacklining practitioners (17 males, 2 females, 25.3 ± 4.9 yo, 70.21 ± 8.79 kg, 1.79 ± 0.05 m) from a faculty of Sport Sciences and a Slackline Club participated in the study. To be included in the sample they had to be able to perform the proposed slackline walking task (see section "Procedures") and respond to the proposed flow scale questionnaire in English language (see section "Procedures"). Before starting, all participants completed a questionnaire to confirm their health status, their dominant/support leg (left, $n = 16$; right, $n = 3$) and subdominant leg, as well as an informed consent form. The experiment was approved by the local Research Ethics Committee.

Procedures

All participants performed a continuous slackline walking task (Gibbon Slackline TM, ID Sports, Stuttgart, Germany) at a freely chosen velocity, without shoes and without falling during 30 s on a band of 10 m long and 5 cm width. They were not exposed to changes in their visual or acoustic information during the trials. They had a maximum of three attempts, separated by a maximum of 5 min rest to accomplish the task. The tension (T) of the slackline's anchors (5.28 ± 0.65 kN), placed at 0.85 m from the ground, was calculated through the following formula:

$$\mathrm{T\,(kN)} = [\mathrm{L\,(m)} \times \mathrm{W\,(kg)}]/[\mathrm{S\,(m)} \times 400]$$

where W is the weight of the participants, L is the length of the slackline (10 m) and S is the sag under load (ensuring at least 0.5 m in the center) (Conley, 2006).

The dynamic stability of the performer-slackline coupling was measured through the temporal variability of the acceleration fluctuations of the ankles, the body segments closer to the slackline, and the CoM, reflecting the postural control during the task. To this end, accelerometer devices WIMU PRO^{TM} (Real Track Systems, Almería, Spain) were placed and fixed with supports on both dominant and subdominant ankles, on the outside part above the lateral malleolus (Mannini et al., 2013), and in the CoM, placing the accelerometer on the zone of L3 (Moe-Nilssen and Helbostad, 2004; Schütte et al., 2016; see **Figure 1**). The acceleration was recorded at a sample frequency of 100 Hz to ensure enough data (>1024) to analyze through Detrended Fluctuation Analysis (DFA) a task lasting 30 s.

The English version of the Flow Short Scale (FSS) (Rheinberg et al., 2003; Engeser and Rheinberg, 2008), validated and applied experimentally to other flow studies (Engeser et al., 2005; Schüler, 2007; Schüler and Brunner, 2009), was administrated at the end of the task. All participants were previously familiarized with the FSS questionnaire. The flow experience (F_{exp}) was measured in ten items (Cronbach's $\alpha = 0.81$) that were divided in two different subscales: the fluency of movements scale (F_{mov}) including items 2, 4, 5, 7, 8, and 9, and the absorption by the activity scale (A) including items 1, 3, 6, and 10.

Data Analysis

Time series for the CoM, the dominant and subdominant leg which were subject to analysis were Euclidean metrics of the 3D Cartesian acceleration components. The Euclidean metrics were directly provided by the accelerometers. The DFA was performed on the data series of acceleration and the Hurst (H) exponent was calculated to assess the temporal structure and time variability properties of the kinematic behavior ($N = 3072$ data points). DFA was conducted as follows (according to Peng et al., 1994, 1995; Ihlen, 2012): first, the total length of the acceleration time series (N) was integrated by using the following equation:

$$Y(i) \equiv \sum_{k=1}^{i} [x_k - x]$$

Where $x_k$is the time series of acceleration and x is the average acceleration of the N data points. A quadratic polynomial function was then used to fit the time series to calculate the local trend (Ihlen, 2012). The resulting, i.e., velocity[4], time series were divided into different windows scales n of equal length, with the local trend being subtracted in each window. The maximum scale of 512 data points was chosen according to Kantelhardt et al. (2002). For each window the root mean square (RMS) fluctuation was calculated by using the following equation:

$$RMS = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left[y(k) - y_n(k)\right]^2}$$

Where the $y(k)$ are the integrated (i.e., velocity) time series and the $y_n(k)$ is the local trend in each box. The H exponent, obtained as the slope value of the linear regression between the scale and local fluctuations on a log-log diffusion plot, was used to determine the temporal structure of the time series fluctuations.

H exponent values in the range $0 < H < 0.5$ were associated with anti-persistent character of velocity fluctuations, while $0.5 < H \leq 1$ values were associated with their persistent profile (Delignières et al., 2011; Ihlen, 2012).

Shared Information Between Flow Scores, Training Frequency/Age and Time-Variability of Kinematic Behavior

In order to detect the degree of shared information between the flow scores (F_{exp}, F_{mov}, and A), the training (ω and τ) variables and behavioral variables (H_{subdom}, H_{dom}, H_{CoM}), we conducted a Pearson correlation (r) and partial correlation analysis (ρ). Then, we performed a series of stepwise regression analyses in order to find out the best explanatory variable(s) responsible for the variance of flow experience scale F_{exp} and its subscales F_{mov} and A, which were treated as response variables.

Potential explanatory variables

ω = training frequency (hours per week): Mean = 2.29 ± 2.98; Min = 0.5; Max = 13

τ = training age (years of training): Mean = 3.05 ± 2.87; Min = 0.5; Max = 13

H_{subdom} = Hurst exponent of the subdominant leg

H_{dom} = Hurst exponent of the dominant leg

H_{CoM} = Hurst exponent of the center of the body mass

Response variables

F_{exp} = flow experience (full scale)

F_{mov} = fluency of movements (subscale)

A = absorption (subscale)

We checked the robustness of the stepwise regression results in three ways. First, we made series of standard simple and multiple regression procedures in order to control for possible confounding or mediating effects within the set of potential explanatory variables (Baron and Kenny, 1986). Second, we performed a series of forward and backward stepwise regression analysis and checked the level of congruence of results. Third, we applied a principal component analysis to highly correlated training variables (ω and τ), to construct a composite linear combination of both sets of standardized scores, in order to manipulate the number of degrees of freedom of the regression model, i.e., the number of potential explanatory variables. In the model including only directly measured variables, there were five potential explanatory variables, and in the model with the principal component there was one less, that is four potential explanatory variables. The variance explained by the explanatory variables was estimated by multiple coefficient of determination R^2. We reported coefficients of multiple coefficient of determination (R^2) adjusted to degrees of freedom of the model. Multiple regression effect sizes were expressed in Cohen's f^2. According to Cohen's (1988) guidelines, $f^2 \geq 0.02$, $f^2 \geq 0.15$, and $f^2 \geq 0.35$ represent small, medium, and large effect sizes,

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[4] Although original time series were acceleration time series, by integrating we obtained the velocity time series. Velocity time series' Hurst exponents (H_v) differ from the Hurst exponents of acceleration time series (H_a) by an additive constant: $H_v = H_a + 1$. Velocity time series, thus, belong to the Brownian motion type ($H_v > 1$) and acceleration time series to a noise type ($0 < H_a < 1$) of fluctuations (Delignières et al., 2011). However, because they differ only by additive constant, the meaning of the results is equivalent for acceleration and velocity profiles.

respectively. Significance level was set on $p < 0.05$. Data analysis was conducted via Matlab© R2013b and Statistica 7 software packages.

RESULTS

The F_{exp} was rated considerably high (5.06 ± 0.89), as its two subscales (F_{mov} = 5.1 ± 1.17; A = 5.01 ± 0.76). The DFA analysis showed a persistent temporal structure of velocity fluctuations in both ankles (H_{dom} = 0.68 ± 0.11; H_{subdom} = 0.71 ± 0.11) and a weakly anti-persistent fluctuations of the CoM (H_{CoM} = 0.49 ± 0.05). **Figure 2** shows two examples of individual time series with persistent and anti-persistent fluctuation dynamics, respectively. Cross-over of the slope, i.e., the Hurst exponent, was not detected (see **Figure 3**). The linear fit to diffusion plot data points in all 19 cases was statistically significant ($p_{min} = 0.03$, $p_{max} = 0.001$) and high ($R^2 = 0.76 \pm 0.02$).

Correlation Analysis of Potential Explanatory and Response Variables

Correlation analysis revealed several important clusters of relationship. F_{exp} showed quite strong association with the subscale F_{mov} ($r = 0.96$; $p = 0.000001$) and strong relationship with subscale A ($r = 0.73$; $p = 0.0009$). Moreover, H_{subdom} and H_{dom} were highly positively correlated ($r = 0.77$; $p = 0.0001$) while showing no correlation with H_{CoM} ($r = 0.24$; $p < 0.235$, and $r = 0.19$; $p = 0.436$), respectively. Also, flow subscales F_{mov} and A were moderately related ($r = 0.50$; $p = 0.03$). Training variables ω and τ showed strong association ($r = 0.71$; $p = 0.001$).

Training frequency (ω) was also moderately associated to most of other variables: F_{exp} ($r = 0.56$; $p = 0.012$); F_{mov} ($r = 0.56$; $p = 0.012$); H_{subdom} ($r = -0.51$; $p = 0.026$) and H_{dom} ($r = -0.57$; $p = 0.01$), while training age (τ) had significant medium relationship only with H_{dom} ($r = -0.49$; $p = 0.034$).

H_{subdom} and H_{dom} showed moderate to high associations with flow scale F_{exp}: ($r = -0.59$; $p = 0.008$); ($r = -0.72$; $p = 0.001$), respectively, and its subscales F_{mov} ($r = -0.55$; $p = 0.015$); ($r = -0.69$; $p = 0.001$) and A ($r = -0.46$; $p = 0.05$); ($r = -0.50$; $p = 0.029$), respectively.

Controlling for joint effects of training variables ω and τ, the associations between the flow scale scores F_{exp} and its subscales F_{mov} ($\rho = -0.93$; $p = 0.00001$) and A ($\rho = -0.69$; $p = 0.002$) decreased. The association of flow scale F_{exp} and the F_{mov} subscale with the H_{dom} variable were maintained: $\rho = -0.59$; $p = 0.013$; $\rho = -0.56$; $p = 0.019$, respectively. Also, the statistically significant relationship between H_{dom} and H_{subdom} was maintained ($\rho = 0.67$; $p = 0.03$).

Controlling for H_{dom}, however, removed the statistically significant associations between training variable ω and the flow scale F_{exp} ($\rho = 0.27$; $p = 0.284$), as well as its subscales F_{mov} ($\rho = -0.28$; $p = 0.265$) and A ($\rho = -0.1$; $p = 0.694$).

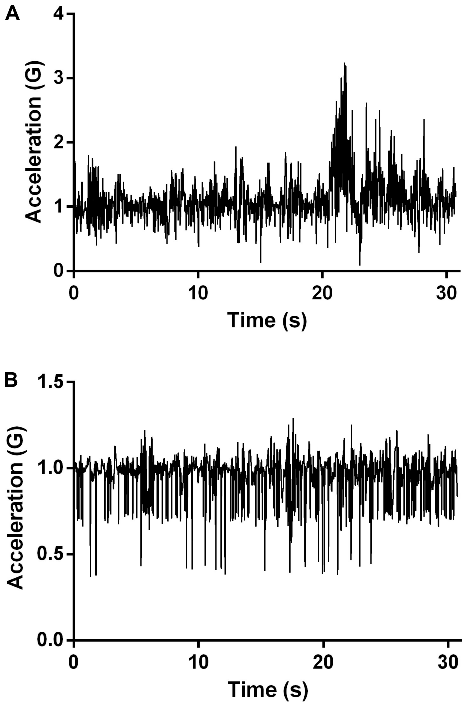

FIGURE 2 | Examples of individual time series with **(A)** persistent (H = 0.89) and **(B)** anti-persistent (H = 0.41) fluctuation dynamics.

Multiple Regression Analysis

In general, the results of the Baron and Kenny (1986) procedure revealed H_{dom} as a potential strong mediating variable. The results were sufficiently robust with respect to changes of the model seeking procedures (stepwise vs. backward) and the manipulation of the degrees of freedom of the model. The backward stepwise procedure revealed identical model to the one obtained by the forward stepwise procedure for the F_{exp} and F_{mov}, but not for A scores. The model degrees of freedom manipulation showed qualitatively the same results, but the statistical significance of the model fit was larger than in forward stepwise regression. However, this model had higher Durbin-Watson statistic and that was the reason to proceed with the interpretation of the original stepwise regression results. Further, we present the results from the forward stepwise regression results noting that the results for absorption scale A have to be taken with more care since they were more fragile with respect to the model used.

Multiple Regression Analysis of Flow-Scale Scores

Tolerance scores of explanatory variables that entered the forward stepwise regression equation, i.e., H_{dom} and ω, were at satisfactory level ($T = 0.67$, $T = 0.67$), respectively. Durbin-Watson statistic ($DW = 2.60$) revealed an independence of residual values. Residuals were also normally distributed (Shapiro-Wilk $p = 0.294$) and satisfied the criterion of homoscedasticity. Cooke's Distance statistic ($D_{median} = 0.03$; $D_{max} = 0.27$; $D_{min} = 0.000001$) showed that there were no influential cases potentially biasing the results.

Multiple correlation between the system of explanatory variables H_{dom}, ω and the F_{exp} scores was statistically significant and strong: $R = 0.74$; $R^2 = 0.49$; $F(2, 16) = 9.63$; $p < 0.002$.

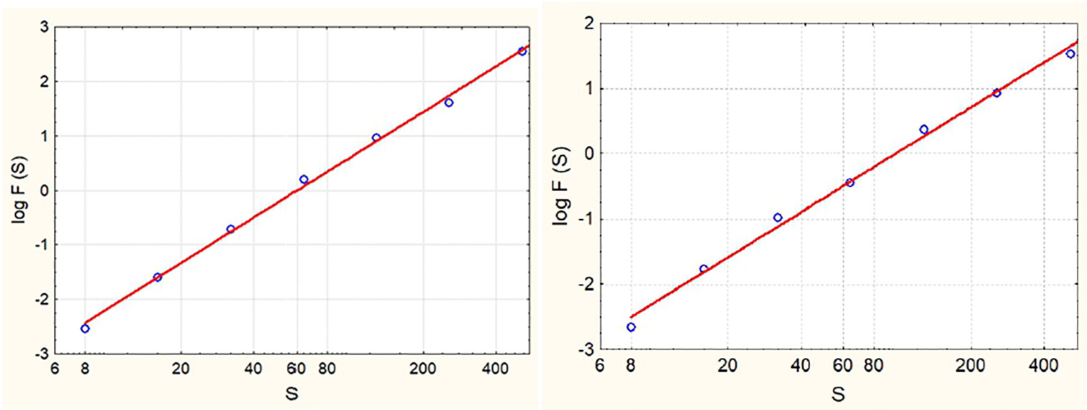

FIGURE 3 | Typical diffusion plots for two participants. F(S) is the magnitude of fluctuations as measured by the RMS (see Eq. 2), and S is the scale.

Cohen's f^2 = 0.96 revealed a very large effect size. Partial regression coefficient was significant only for H_{dom} ($\beta = -0.58$; $t(16) = -2.84$; $p < 0.01$), but for ω showed no statistically significance ($\beta = -0.23$; $t(16) = 1.11$; $p < 0.284$).

Multiple Regression Analysis of Fluency of Movements Subscale Scores

Tolerance scores of explanatory variables who entered the forward stepwise regression equation H_{dom} and ω were ($T = 0.67$, $T = 0.67$), respectively. Durbin-Watson statistic ($DW = 2.68$) revealed an independence of residual values. Residuals were also normally distributed (Shapiro-Wilk $p = 0.76$) and satisfied the criterion of homoscedasticity. Cooke's Distance statistic ($D_{median} = 0.03$; $D_{max} = 0.14$; $D_{min} = 0.002$) showed that there were no influential outliers potentially biasing the results.

Multiple correlation between the system of explanatory variables H_{dom}, ω and the F_{mov} scores as response variable was statistically significant and strong: $R = 0.72$; $R^2 = 0.46$; $F(2, 16) = 8.68$; $p < 0.003$; $f^2 = 0.85$ signified a very large effect size. However, partial regression was significant only for H_{dom} ($\beta = -0.553$; $t(16) = -2.61$; $p < 0.019$), and showed no statistical significance for ω ($\beta = -0.245$; $t(16) = 1.16$; $p < 0.26$).

Multiple Regression Analysis of Absorption Subscale Scores

Tolerance scores of explanatory variables which entered the regression equation: H_{dom} and H_{CoM} were ($T = 0.94$, $T = 0.94$), respectively. Durbin-Watson statistic ($DW = 2.07$) revealed the independence of residual values. Residuals were also normally distributed (Shapiro-Wilk $p = 0.28$) and satisfied the criterion of homoscedasticity. Cooke's Distance statistic ($D_{median} = 0.014$; $D_{max} = 0.86$; $D_{min} = 0.0002$) showed that there were no influential cases potentially biasing the results.

Multiple correlation between the system of explanatory variables H_{dom}, H_{CoM} and the A scores as response variable was statistically significant and of medium strength: $R = 0.58$; $R^2 = 0.25$; $F(2,16) = 4.00$; $p < 0.039$. Nevertheless, Cohen's test ($f^2 = 0.33$) revealed medium effect size. However, partial contributions of both variables were not significant, although H_{dom} was a borderline case: ($\beta = -0.43$; $t(16) = -2.05$; $p < 0.057$) and ($\beta = -0.297$; $t(16) = -1.41$; $p < 0.177$).

DISCUSSION

The aim of the current study was to capture the effects of correspondence within the bi-directional continuous perception-action cycle of a slackline walking task. The correlation analysis showed some intriguing relations between the treated variables. F_{exp} was dominantly associated to the fluency of movements subscale F_{mov} and less to absorption subscale A. After controlling for effects of training variables ω and τ and action variable H_{dom}, the differences of these associations increased. Moreover, controlling for training variables maintained the statistically significant association between the action variable H_{dom} with the flow scale F_{exp} and its fluency subscale F_{mov}, while controlling for H_{dom}, removed the significant associations between training variables ω and τ and the flow scale F_{exp} and its subscales F_{mov} and A. This may mean that it is the *information related to action* (i.e., the pragmatic information) which is the main constituent of the informed awareness of flow experience for this task. The regression analysis also consistently revealed H_{dom} as an explanatory[5] variable of the flow experience (the full scale and its subscales), although the absorption subscale A showed larger part of specific variance in comparison with the fluency of movements subscale F_{mov}. Absorption refers to a task engagement with minimal self-consciousness when demands and skills are in balance (Rheinberg and Vollmeyer, 2003; Peifer et al., 2014). The constraints of the slackline walking task may have not been able to induce such type of dominant outward focused attention in performers. It is probable that the slackline task is, to a certain degree, demanding of self-internally focused attention. Focusing on the body-slackline mechanical contact, i.e., enabling crisp self-information from tactile and

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[5] For both subscales and the full scale the unexplained, i.e., flow unique variance, was probably due to individual history differences, unaccounted specific constraints impinging on the perception-action system (Balagué et al., 2019), as well as the error variance.

proprioceptive sources (Shaw and Kinsella-Shaw, 2007), may be crucial for accomplishing the task.

Indeed, slackline walk is commonly used as a meditative (mindfulness) practice (Curtis and Braga, 2018) which requires increased self-awareness. On the other hand, the flow experience, by its definition, requires reduced self-consciousness (Sheldon et al., 2015). It may be that there was a trade-off relation between these conflicting requirements for absorption, responsible for the results obtained in this specific task. This finding calls to attention to the possibility of varying degrees of involvement of movement fluency (sense of control) and absorption processes for the flow experience in different tasks.

Taking together these results with those of the correlation analysis, we can go a step further claiming that perception-action-environment processes, responsible for determining the values of H_{dom}, have a causal role in forming a flow experience, as constitutive of the informed awareness of participants. In this case H_{dom} would play a role of a nearly full mediator variable between the rest of explanatory variables and the response variables (flow scores). Neither training age nor frequency of training significantly predicted the flow scores (subscales and the full scale). Their effects, as well as the effect of H_{subdom} on the flow experience, were clearly mediated by the H_{dom} variable. The temporal structure of fluctuations of the whole coupled body-environment (i.e., slackline) system, as measured by H_{dom}, co-varies with and corresponds to the states of informed awareness (particularly the perception of fluency of movements). Note that these processes are not *only* neurologically regulated and even less they are skull bound. In other words, the changes in body-slackline coupling, i.e., the body-environment dynamics, as measured by H_{dom}, regulate the flow experience. Any deviation from the locally optimal attunement to the walk-on-ability-affordance creates a state that has to be stabilized by compensatory actions. Compensatory actions are a result of online explorations of stability. There is hardly a pre-set value, a mental representation of a "correct" action or action sequence that can be applied. A pre-set correct action simply cannot exist because there is an ever changing unpredictable flow of the performer-slackline interactions. What is important is to locally solve the perceptual attunement and action on the walk-on-ability affordance. Hence, all perceptual explorations and compensatory movements are made "on the fly" as a result of a successful contingent perception-action explorations. If these compensatory perception-action cycles come close to bring about instability in the performer-environment coupling they destroy the flow awareness and vice versa. Thus, flow and particularly the fluency of movements experience does not correspond to "*automaticity*"[6] of actions (see Harris et al., 2017 for opposite opinion), but to their functional flexibility, i.e., *adaptability*. Note again that the flow experience, as a part of the informed awareness *itself*, does not have to contain any propositional properties, but nonetheless can, to a degree, be captured by linguistically engaged performers, using propositional statements given in the questionnaire. In this sense, the flow experience *itself* can be defined not as merely skull bound mental state, but as embodied and extended active process of informed awareness emerging at the level of performer-environment system.

While the velocity fluctuations of the ankles showed persistent fluctuations, the velocity fluctuations of the CoM showed dominantly anti-persistent behavior. The persistent dynamics reflects a more balanced interaction of negative and positive feedback loops within the system, and the anti-persistent dynamics a dominance of the negative-stabilizing feedback (Cuomo et al., 2000; Vázquez et al., 2016). The persistent time variability structure of the ankle's velocity fluctuations reflected an exploratory and compensatory synergy of lower limbs to regulate the balance of the CoM on the webbing. In contrast, the anti-persistence of the CoM fluctuations signified its tightly controlled stability that has been enabled by different compensatory synergies reflected in ankle fluctuations (Latash et al., 2007; Singh et al., 2018). In general, it seems that the lower limbs explore possible coordination in order to form a negative feedback for the efficient positional control of the performer's CoM. This points to the possibility that performers experiencing low flow need larger movement explorations (leg excursions) to acquire a functional control of the body's CoM. On the contrary, high flow performers need less exploratory actions (less leg excursions) to attain the control. These differences signified variations in embodied cognitive strategies of performers while negotiating task constraints. The increased positive correlation of increments in the time series has been formally connected to the phenomenon of critical slowing down, i.e., the impending instability of the complex system, indicating the loss of system's resilience (Scheffer et al., 2012). Thus, higher H values meant that, on average, positive serial correlations were larger and thereby there was a more emphasized critical slowing in the system (Vázquez et al., 2016). This means that the performer-slackline system of participants with higher H values was less stable (i.e., increased the chances of critical transition, fall or task disengagement) than those with lower H values.

On the other hand, even a novice with several months of training may become well adapted to the constraints of the current task and release the attentional resources partly outward. One may hypothesize that a larger height or lower tension of the slackline, or both, would form a task with higher level of functional difficulty. Suitably modified task constraints may induce more direct effects of the training age and frequency of training on flow experience. Such task constraints may particularly affect effects of behavioral movement action variables such as H_{dom} on the absorption subscale scores due to larger salience of task internal related focus of attention in more challenging situations tasks of this type. These hypotheses warrant further investigation on a larger sample of performers.

The adaptability to environmental changes characterizes successful performers, because their system's stability is reflected in their capacity to negotiate the induced perturbations through stable but flexible coordinated movements (Davids et al., 2012; Santuz et al., 2018). Even good performers need compensatory movement variability (Davids et al., 2012). Such performance conditions involve a coordinated

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[6] Automaticity, on the other hand, may be attained in stable, attentionally non-demanding environments. It does not require a strong action-related attention focus and may allocate the attention resources to task unrelated thoughts (e.g., Balagué et al., 2012).

action to integrate functionally the degrees of freedom of the performer-environment system (Davids et al., 2008). This integration is dynamically formed by the reciprocal interaction among the slower and shorter time-scale control loops of the performer-environment system (Hristovski and Balagué, 2010; Vázquez et al., 2016).

As slackline is not a regulated and competitive activity that performers practice regularly, the participants in this study could not be classified according their performance results, as was done in previous research (Den Hartigh et al., 2015). Regarding the retrospective self-report method used in this study, limitations should be also taken into account. Due to it, more research is warranted to confirm the current results. Moreover, a research based on bi- or multivariate time series of flow experience scores and behavioral quantities may provide in future more detailed and more realistic understanding of the continuous dynamic entanglement of processes which form the experience-behavior complementary pair.

In conclusion, as a first step toward the goals expressed in the previous passage, the stable co-variance of perception-action variables signified the embodied nature of the flow experience. The dynamic signatures of the whole performer-environment system, such as the critical slowing down, strongly affected the flow experience. In this sense, it is the ecological dynamics of the whole performer-environment system and the fluctuating dynamics of the continuous multi timescale perception-action cycles within it, that characterizes the experience of flow as a state of the informed awareness (Shaw and Kinsella-Shaw, 2007).

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Comité d'Ètica d'Investigacions Cliniques de l'Administració de Catalunya. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

NB, RH, LR, and LM conceived and designed the experiments. LM, LR, and NB performed the experiments. LM, PV, and RH analyzed the data. RH, LM, PV, and NB interpreting the results. LM, LR, PV, and NB contributed the reagents, materials, and analysis tools. LM, PV, NB, RH, and LR wrote the manuscript.

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Dynamics of Experience in a Learning Protocol: A Case Study in Climbing

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Many of the studies on motor learning have investigated the dynamics of learning behaviors and shown that the learning process is non-linear, self-organized, and situated. Aligned with this research trend, studies within the enactive paradigm focus on learners' lived experience to understand how it shapes their intentions, actions, and perceptions. Thus, a joint analysis of experiential and behavioral assessments might help to explain the dynamics of learning (e.g., the transition between stable states). The aim of this case study was to analyze the dynamics of a beginner climber's lived experience as his performance progressed (i.e., climbing fluency) during a learning protocol. The protocol comprised 10 climbing sessions over 5 weeks. During the sessions, the climber had to climb a "control route" (CR) (i.e., a route that never changed) and "variants" (i.e., novel routes, in which the spatial layout of the holds was modified). Phenomenological data were collected with self-confrontation interviews after each session. From the verbalizations, a thematic analysis of the climber's intentions, actions, and perceptions was performed to detect the general dimensions of his experience. The behavioral data (the climber's performance) were assessed using four indicators of climbing fluency: climbing time (CT), immobility ratio (IR), geometric index of entropy (GIE) of the hip trajectory, and the jerk. Our results highlighted the dynamics of the climber's lived experience and performances in the unchanged and novel environments. The dynamics on the CR were characterized by four crucial episodes and the dynamics on the variants, by four ways of experiencing novelty. Our results are discussed around three points: (i) the climber's definition of his enacted fluency in terms of intentions, actions, and perceptions; (ii) how the definition was identified through a dynamic phenomenological synthesis; and (iii) three effects that characterize the dynamics: challenge, metaphor, and a refinement in perceptions.

Keywords: learning, enaction, phenomenology, climbing, embodiment

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INTRODUCTION

Grasping the Complexity of Learning Through Behavioral Modifications

The embodied approaches to motor learning conceive of learners as complex neurobiological systems (Chow et al., 2009) showing intrinsic self-organizing dynamics that constitute a repertoire of stable and spontaneous behaviors (Kostrubiec et al., 2012). This repertoire enables learners to adapt effectively to environmental and task constraints (Newell, 1986). From this perspective, learning is the reorganization of stable behaviors, with intrinsic dynamics perpetually being destabilized and reorganized as a function of the constraints (Zanone and Kelso, 1992). Learning in this sense is characterized by the non-linear dynamics of transitions from one stable coordination pattern to another (Schöner et al., 1992). During these transitions, new behaviors may temporarily alternate with previous behaviors in a so-called "intermittent regime" and are accompanied by an interplay of regressions and progressions in "measurable" performance (Nourrit et al., 2003; Teulier and Delignières, 2007). These periods of intermittent regime are nevertheless functional as they indicate the learner's exploration and exploitation of new coordination solutions to achieve the task (Chow et al., 2011; Komar et al., 2019). This perspective led to the development in non-linear pedagogy (Chow, 2013) using a constraints-led approach (Davids et al., 2008), where teachers and/or practitioners manipulate a set of constraints (i.e., environment and task) in order to prompt improvements in the quality of learners' explorations and thereby provoke the development of adaptable behaviors (Komar et al., 2019). In addition, the evidence is growing that learning is characterized by individual pathways in the interactions with constraints (Pacheco et al., 2017; Pacheco and Newell, 2018). These insights from dynamical systems theory and non-linear pedagogy suggest questions about whether learners live meaningful perturbations during the intermittent regimes or instead perceive a step-by-step or linear progression. In addition, it can be assumed that each individual has his/her own way of experiencing constraints and appropriating the design of the task. Individualized pathways can therefore be investigated at the level of the learner's lived experience, as proposed by the enactive paradigm, which conceives individuals as embodied agents who meaningfully interact with the environment (Di Paolo, 2009).

Learning as a Lived Experience: Shedding Light on Meaningful Transformations

The enactive paradigm (Varela et al., 1991; Stewart et al., 2010) conceives human cognition as consisting of the construction of significations that emerge from the continuous interaction between an actor and his/her environment (i.e., actor–environment coupling). These significations refer to the actor's point of view about the environment, with which he/she interacts in function of his/her past experiences and his/her involvement in the situation. While the enactive paradigm shares the ideas of self-organization, non-linearity, and constraints traditionally defended by dynamical systems theory, it proposes a conception of cognition that is rooted in action, meaning that an actor brings forth (i.e., enacts) a meaningful situation from his/her coupling with the environment. Specifically, it conceives the actor–environment coupling as asymmetrical because the relationship with the environment is partly regulated by the actor's lived experience. The core ideas about cognition within the enactive framework suggest that cognition can be investigated as: (i) fundamentally embedded in an environment in which constraints need to be regulated by the cognitive system; (ii) autonomous, as it emerges from ongoing structural couplings with the environment that define its own organization; (iii) embodied, which means that the bodily structures are key components of perceptions and actions; and (iv) regulated by a sense-making process, which means that the agent generates meaning and "casts a web of significance on [the] world" (Di Paolo et al., 2011, p. 39). To grasp how the actor builds meaning, we focus on pre-reflective consciousness, defined by Theureau (2006) as the level of consciousness at which an actor can show, mime, simulate, tell about, and comment on his/her activity in favorable conditions. In sports psychology, the potential of analyzing athletes' activity via their pre-reflective consciousness has resulted in a growing number of studies (Sève et al., 2005; Hauw and Durand, 2007; Mohamed et al., 2015; Rochat et al., 2017) that provide practical recommendations for preparing, training, and managing competitions. We may thus expect that this approach applied to the learning process will yield practical recommendations for designing learning environments. Indeed, the analysis of lived experience has been shown to be helpful for designing computer-assisted learning environments (Leblanc et al., 2001), professional training and lifelong education programs (Durand, 2015), and elite sports preparation (Durand et al., 2005; Hauw, 2018).

Lived Experience and Behavior as Complementary Domains of Evidence to Understand the Dynamics of Learning

Varela and Shear (1999) stated that lived experience is irreducible, which means that the pre-reflective phenomena that are brought forth by the actor "cannot be reduced or derived from the third-person perspective" (p. 4). Lived experience (i.e., the first-person) is thus in itself a domain of evidence just as much as the behavioral (i.e., third-person) domain. These authors therefore proposed that the circulation between the first- and third-persons would provide reciprocal contributions. From this perspective, accessing learners' subjectivity at the phenomenological level would help to reconstruct their meaningful activity (i.e., their intentions, interpretations of the situation, focalizations, emotions, significations given to the unfolding action and the situation), and this would be accomplished in a mutually enriching relationship with the third-person indicators. Such phenomenological approaches have indeed been used to highlight that the dynamics of performers' lived experience and behavior may be either convergent or divergent. For example, Sève et al. (2013) studied the lived experiences of rowers and identified their difficulties in synchronizing with their partners.

These authors further found that the difficulties converged with kinematic measures indicating differences in stroke amplitudes and angular velocities between the rowers. A swimming study on the use of an underwater technical device (i.e., the MAD system) highlighted divergences between what was lived by the swimmers and the biomechanical measures of their movement (i.e., the force applied by the hands on the pads) (Gal-Petitfaux et al., 2013). In both these examples, the phenomenological data provided access to the way the actors created meaning about their activity and, when applied to learning, such data might well reveal the exploration strategies undertaken by learners. This in turn would help assess the effectiveness of exploration strategies and their impact on the intermittent regimes.

In the present study, we jointly investigated a learner's lived experience and performances to (i) enrich the analysis of learners' experience with third-person data in order to objectivize the transformations linked to learning, and (ii) examine the possible differences/divergences between what is objectivized and what the actor lives. To attain this goal, we used a phenomenological approach that attempts to address the complexity of the non-linear dynamics of learning by giving importance to what the learners live without, however, excluding the third-person data that provide access to the intermittent regimes. Therefore, the present study, which is based on the principles of self-organization and non-linear dynamics, seeks to understand how these principles manifest in a learning situation in climbing, mainly from a phenomenological and enactive point of view but not exclusively. We propose a case study of a beginner climber following a learning protocol characterized by variable practice (i.e., climbing on unchanged and novel climbing routes) in order to characterize how he deals with the novelty of the environment. During the protocol, we followed his lived experience at the pre-reflexive level in relation to his performances (i.e., his climbing fluency). By doing so, we sought to understand how he embodied climbing fluency in terms of intentions, actions, perceptions, and performances. In sum, we sought to model the phenomenology of learning dynamics as a function of the novelty of the encountered situations and propose an integrative approach that articulates lived experience and recorded behaviors during the performance of a climbing task: climbing the whole route as fluently as possible with variable practice (i.e., novelty during learning when the climbing route is changed). We assumed that the results would have a twofold impact: first, for the development of integrative research methods to investigate learning, where learners' points of view are taken into account, and second, for designing appropriate learning situations to prompt beginners to effectively explore their environment.

MATERIALS AND METHODS

Research Design

The present research is a case study that mobilizes a methodology that is able to pick up the modifications in a learner's lived experience in relation to the progress in his performances throughout a learning protocol. By considering the phenomenon under study as inseparable from its context, we expected to provide a detailed analysis of (i) what is typical, recurrent, and crucial in the learner's experience and (ii) the transformations in the learner's own world (i.e., the meaningful situation enacted by him/her) from a dynamical and situated perspective. Hence, our intention was not to generalize the results stemming from this analysis, but rather to propose a methodology integrating two domains of evidence (i.e., for future research, this type of analysis might be feasible for larger samples of participants and for other learning protocols).

Participant

The participant was a 20-year male volunteer (height: 174.5 cm, weight: 66 kg, arm span: 178 cm, right-handed). He was an undergraduate student at the sports faculty of Rouen Normandy University but had no prior experience in climbing. The protocol was explained to the participant and he gave his written informed consent before starting the experiment.

Protocol

The protocol was composed of 10 climbing sessions (i.e., two sessions per week) on an artificial wall in the gym facilities of Rouen Normandy University. This artificial wall had three routes dedicated to the protocol. One route, which never changed, was called the "control route" (CR) and was 525 cm high with 20 holds (i.e., 13 handholds and 7 footholds). The CR was the unchanged environment. The first three climbs of every session were performed on this route. The other two routes were on a wall 480 cm high and each also had 20 holds. These two routes were called "variants" (V) as they changed every two sessions. A total of nine variants were applied during the protocol. Six trials per variant were performed during two successive sessions (**Table 1**). These variants were the novel environments. A total of 30 trials were performed on the CR and 54 on the variants. Importantly, when designing the variants, we changed the spatial layout of the handholds but did not manipulate the difficulty of the routes. Also, the shape of the holds was always the same. When the other two routes were not used, they were covered with a tarpaulin so that only the route to be climbed was visible. Before each climbing session, the participant had a 10-min warm-up on easy boulder routes in the bouldering area of the climbing gym. Before each climb, the climber had a 30-s preview that he could use completely or not. Prior to each climb, the following instructions were given: "Use all the handholds in a bottom-up order, do not to use holds with both hands or both feet at the same time. In addition, you have to find a way to climb the route as fluently as possible: that is, avoiding pauses and saccades." At the beginning of each session before the warm-up, the climber was given feedback about his climbing fluency (see the section "Behavioral Data Processing" for more detail). Each session lasted 1 h on average, including the warm-up, equipping the participant, giving him the instructions before each trial with previews and climbs, and launching the cameras and the inertial measurement unit (IMU) recordings for each trial (see the section "Behavioral Data Collection" for more detail). The participant also performed a transfer route in sessions 1 and 10, but these results are not presented for the present study, as we focus here on

TABLE 1 | Organization of the learning protocol.

Week 1		Week 2		Week 3		Week 4		Week 5	
Session 1	**Session 2**	**Session 3**	**Session 4**	**Session 5**	**Session 6**	**Session 7**	**Session 8**	**Session 9**	**Session 10**
10-min warm-up	10-min warm-up	10-min warm-up	10-min warm-up	10-min warm-up	10-min warm-up	10-min warm-up	10-min warm-up	10-min warm-up	10-min warm-up
1xTR	3xCR	3xCR	3xCR	3xCR	3xCR	3xCR	3xCR	3xCR	3xCR
3xCR	3xV1	3xV2	3xV3	3xV4	3xV5	3xV6	3xV7	3xV8	3xV9
3xV1	3xV2	3xV3	3xV4	3xV5	3xV6	3xV7	3xV8	3xV9	1xTR
Interview	Interview	Interview	Interview	Interview	Interview	Interview	Interview	Interview	Interview

This table presents the organization of each session (1–10) of the learning protocol. Each session contained a 10-min warm-up and was followed by an interview. Each square shows the number of trials performed on the different routes: control route (CR); variant 1 (V1); variant 2 (V2), etc. In the first and last trials, the participant performed a transfer route (TR).

the learning dynamics and not on what was transferred between pre- and post-learning.

Data Collection

Phenomenological Data Collection

Phenomenological data were collected immediately after each session with self-confrontation interviews based on the video recordings of each preview and climb (Hauw and Durand, 2007; Adé et al., 2017). These video recordings were used as past-activity traces to help the climber re-enact his past experience as it emerged during the climbs. This means that he was invited to chronologically relive his meaningful experience throughout the climbing trials. On the basis of these traces, the interviews consisted of asking him to comment his activity during the previews and climbs, avoiding retrospective judgments and generalizations. Especially, the interview prompts aimed to document (i) the climber's intentions (what are you trying to do?), (ii) his actions (what are you doing?), and (iii) his perceptions (what is drawing your attention? What are you feeling?). The interviews were conducted by two trained researchers who were experienced in conducting self-confrontation interviews with athletes from different sports. In total, 10 1.15-h interviews were conducted for the present study.

Behavioral Data Collection

Behavioral data were collected for each climb to compute the climber's fluency scores. The participant wore a light and an IMU (HIKOB FOX®, Villeurbanne, France) on the back of his harness. The sensor recorded the signal from an accelerometer, a gyroscope, and a magnetometer at 100 Hz. Ascents were filmed at 29.97 fps on 1920 × 1080 pixel frames with GoPro Hero 5® (GoPro Inc., San Mateo, CA, United States) cameras covering each entire wall (i.e., one camera per wall). The holds of the route were instrumented with the Luxov® Touch system[1] (Arnas, France) that uses a capacitive sensing technology to detect and record the time of contact on each hold. For the present study, these data (i.e., the signal of the touch) was used only to compute the climbing time (CT) (from the climber's first movement – either with a hand or foot – from the starting position until he touched the last handhold).

Data Processing

The data were processed in two successive steps: the first step consisted of separate processing of the phenomenological data and the behavioral data, and the second step consisted of portraying the learning dynamics from the combination of these two types of data.

Phenomenological Data Processing

The phenomenological data were processed in three steps: (i) semiotic labeling of the climber's course of experience, (ii) thematic analysis of the course of experience, and (iii) analysis of the phenomenological dynamics. Each step was co-jointly performed by the first, third, and last authors, who were all trained in performing this type of phenomenological data processing. In case of disagreement, the researchers re-watched the video recordings of the self-confrontation interviews and the climbs and debated until a consensus was found. First, we restored the climber's course of experience for each of his 84 climbs. This consisted of a semiotic labeling of his intentions, perceptions, and actions from his verbalizations in the self-confrontation interviews and the climbing activity recorded on the videos [as already done in Rochat et al. (2018), for trail running and Seifert et al. (2017), for rowing, for example]. Second, similar to R'Kiouak et al. (2016), we conducted a thematic analysis to inductively find similarities in the climber's intentions, actions, and perceptions (Braun and Clarke, 2006; Vaismoradi et al., 2013) in order to characterize the general dimensions that made up his course of experience and his definition of his enacted fluency. The raw data of the intentions, actions, and perceptions were examined in detail and the detection of similarities among them helped identify the first-order themes, which were merged into second-order themes, and then general dimensions. The identified themes enabled us to inductively characterize the general dimensions, which indicated the modalities by which fluency was meaningfully enacted in terms of intentions, actions, and perceptions (**Figures 1–3**). For this stage of the processing, we applied thematic analysis to each category of the course of experience (i.e., the intentions, actions, and perceptions) separately to arrive at an intelligible synthesis of the elements that were meaningful for the climber. Third, to characterize the phenomenological dynamics on the CR and on each of the nine variants, we (i) reconstructed the climber's courses of

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[1] http://www.luxov-connect.com/en/products/#touch

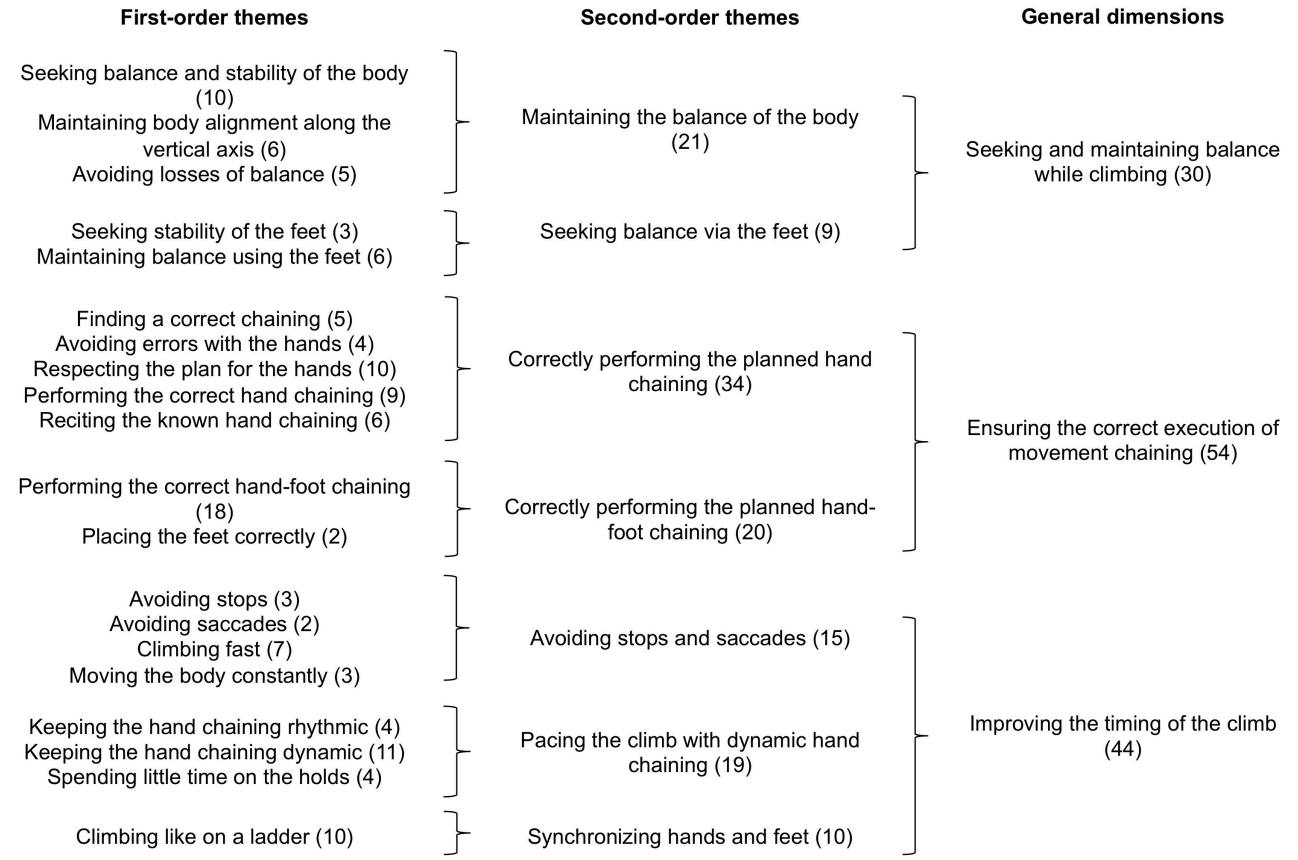

FIGURE 1 | Thematic analysis of the climber's intentions. The first column presents the first-order themes. The second column presents the second-order themes (i.e., merging of the first-order themes). The third column presents the general dimensions (i.e., merging of the second-order themes). The numbers in parentheses associated with each theme refer to the number of occurrences identified from the verbalizations.

experience with the combination of the general dimensions of the intentions, actions, and perceptions for each trial, and (ii) tracked the cumulative sum of each general dimension throughout the trials in order to obtain their dynamics of emergence. The processing was done on RStudio 1.1.383 that used R version 3.5.1 (**Figures 4–8**).

Behavioral Data Processing

To assess the climbing performance of each trial, we relied on four indicators that included CT (i.e., from the moment when the climber touched another hold from that of the initial position to the moment when the last handhold was touched) and three fluency indicators: (i) the immobility ratio (IR), which is a temporal indicator that refers to the percentage of CT spent immobile (Seifert et al., 2015; Orth et al., 2018), (ii) the geometric index of entropy (GIE) of the hip trajectory, which is a spatial indicator that refers to "the degree of coherence of the action–perception coupling" (Cordier et al., 1994, p. 748), and (iii) the jerk of hip orientation, which is a spatiotemporal indicator (Seifert et al., 2014). By combining these indicators, we sought to determine whether climbing fluency was impacted by spatial factors (i.e., searching the route), temporal factors (i.e., searching the best way to grasp a hold), or spatiotemporal factors (i.e., transiting between holds). The percentage of CT spent immobile was based on a hip velocity threshold (set at 20 cm/s) (Orth et al., 2018, p. 8). The GIE refers to the length of the hip trajectory divided by the length of its convex hull to which a logarithmic transformation is applied. This index reflects the complexity of the hip trajectory. To assess the GIE, the harness light was video-tracked on Kinovea© software (version 0.8.25, Boston, MA, United States) to obtain the climber's coordinate of hip trajectory projection on the 2D wall. The camera lens distortion was compensated by importing the intrinsic parameters of the camera, and the video perspective was corrected using a manually set grid-based calibration on this software. The jerk of hip orientation corresponds to the third derivative of the hip orientation and informs about the spatiotemporal fluency (Seifert et al., 2014). All processing was performed with MATLAB R2014a® software (version 8.3.0.532, The MathWorks Inc., Natick, MA, United States). The scores for spatial immobility, GIE, and jerk for each climb were given as feedback to the participant in the subsequent climbing session (e.g., the scores in session 1 were given at the beginning on session 2 and so on). From the score values, three terciles were computed to express the climber's performance. The values included in the first tercile corresponded to his best scores, the values in

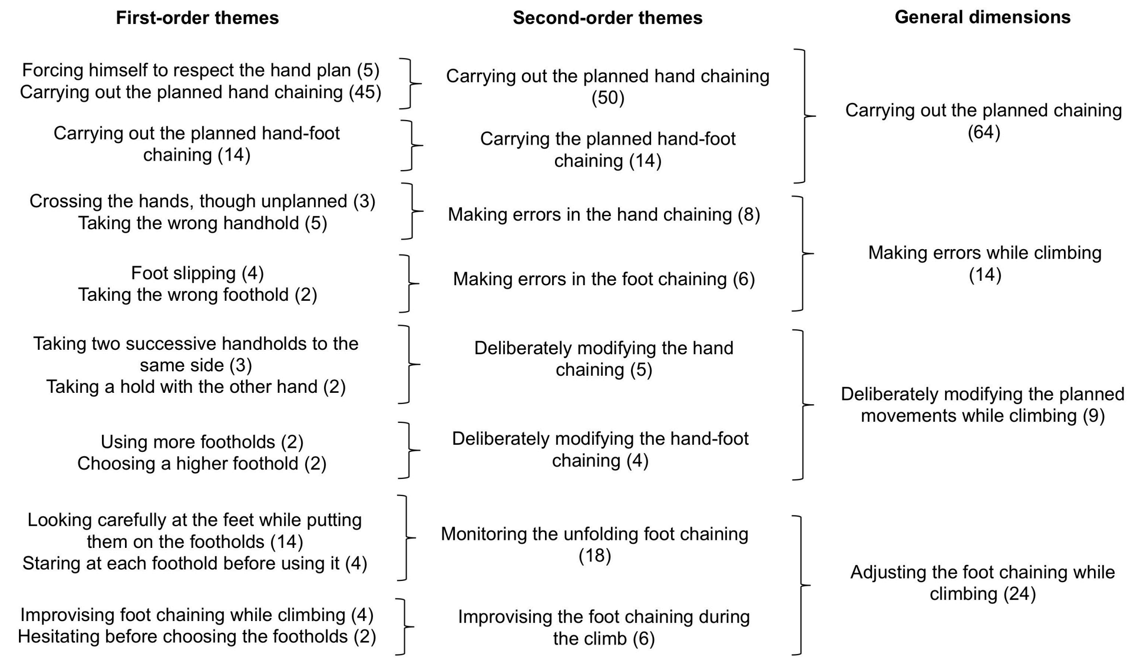

FIGURE 2 | Thematic analysis of the climber's actions. The first column presents the first-order themes. The second column presents the second-order themes (i.e., merging of the first-order themes). The third column presents the general dimensions (i.e., merging of the second-order themes). The numbers in parentheses associated with each theme refer to the number of occurrences identified from the verbalizations.

the second tercile corresponded his intermediate scores, and the values in the third tercile corresponded to his poorer scores. It must be noted that for the four indicators of fluency, the lower the scores were, the better the performance was, and inversely. In order to obtain a more accurate delimitation of the terciles, the computations were conducted on the CR and variants separately. Therefore, each tercile contained the ranges of values displayed in **Table 2**.

Characterization of the Dynamics of the Phenomenological and Behavioral Data: A First-Person Entry

In this step of the data processing, the dynamics of emergence of the general dimensions identified in the phenomenological data were synchronized with the progression in the fluency scores on CR and each variant separately. This step had a twofold aim: (i) to characterize the salient episodes that made up the learning dynamics in the unchanged and novel environments, and (ii) to determine the congruence/divergence between the climber's experience and his actual performance scores. We therefore focused on when the climber perceived a meaningful perturbation in his climbing fluency, and we qualitatively characterized each episode on the basis of his verbalizations during the interviews. We then took into account the scores in these episodes to investigate whether they were congruent or divergent with his perceived fluency. Importantly, as already observed in previous studies that have articulated phenomenological data with behavioral data (e.g., Gal-Petitfaux et al., 2013; R'Kiouak et al., 2016; Seifert et al., 2017), we were not necessarily expecting a fully congruent relationship between what had been meaningfully experienced and what had been behaviorally performed.

Ethics Statement

The protocol followed the guidelines of the Declaration of Helsinki. Procedures were explained to the participant who then gave his written consent to participate.

RESULTS

The results are presented in three parts. The first part presents the characterization of the climber's enacted fluency based on the thematic analysis of his course of experience. The aim of the thematic analysis was to characterize the climber's definition of his enacted fluency. The second part presents the phenomenological dynamics of the climber's enacted fluency (i.e., the tracking of the temporal emergence of the general dimensions) in association with his fluency scores in the unchanged environment. The third part presents the phenomenological dynamics of the climber's enacted fluency in association to his fluency scores in the novel environments. The fluency scores values are presented in the **Supplementary Material**.

The Climber's Enacted Fluency

Intentions

The results of the thematic analysis of the climber's intentions revealed three general dimensions (**Figure 1**): (i) Seeking and

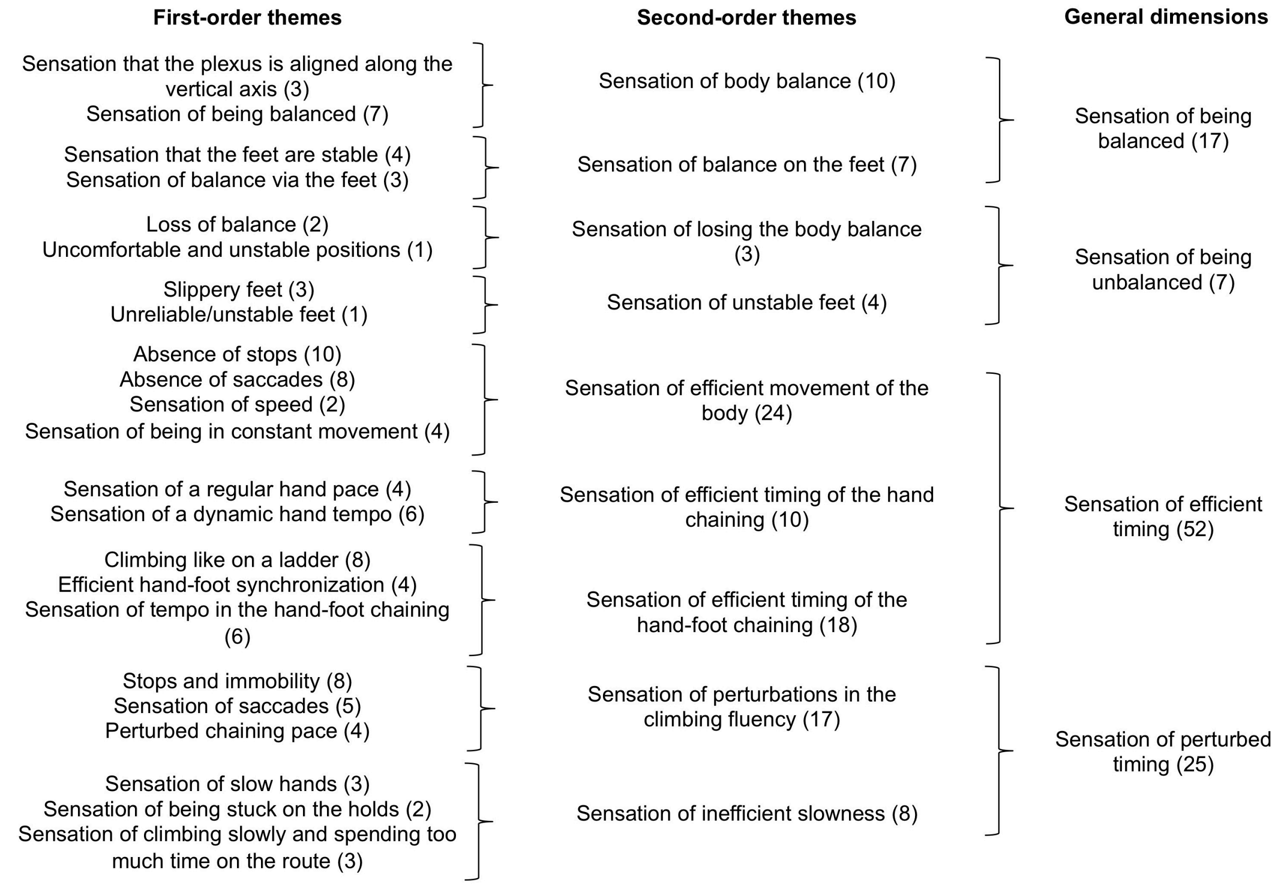

FIGURE 3 | Thematic analysis of the climber's perceptions. The first column presents the first-order themes. The second column presents the second-order themes (i.e., merging of the first-order themes). The third column presents the general dimensions (i.e., merging of the second-order themes). The numbers in the parentheses associated with each theme refer to the number of occurrences identified from the verbalizations.

maintaining balance while climbing, (ii) Ensuring the correct execution of movement chaining, and (iii) Improving the timing of the climb. The general dimension Seeking and maintaining balance while climbing referred to the climber's concerns about avoiding losses of balance, which would have threatened climbing fluency. This intention involved either the whole body or the feet. The general dimension Ensuring the correct execution of movement chaining referred to the climber's concerns about finding and correctly performing a chaining of movements and avoiding errors to ensure fluency. This intention involved either hand chaining or hand-foot chaining. The general dimension Improving the timing of the climb referred to the climber's concerns about avoiding stops and saccades and pacing his movements with dynamic movements in order to improve fluency. This intention involved either hand movements or hand-foot synchronization.

Actions

The results of the thematic analysis of the climber's actions revealed four general dimensions (**Figure 2**): (i) Carrying out the planned chaining, (ii) Making errors while climbing, (iii) Deliberately modifying the planned movements while climbing, and (iv) Adjusting the foot chaining while climbing. These general dimensions encompassed the climber's meaningful actions during his climbs; it is important to note that for a given climb, several actions may have been performed simultaneously (e.g., carrying out the planned hand chaining while adjusting the foot chaining). The general dimension Carrying out the planned chaining referred to the climber's actions corresponding to the movements he had planned during the preview. These actions concerned either the hand chaining or the hand-foot chaining. The general dimension Making errors when climbing referred to the climber's unplanned actions, which he lived as errors. These meaningful errors involved either the hands (i.e., taking a wrong handhold or crossing the hands) or the feet (i.e., taking a wrong foothold or a foot slipping). The general dimension Deliberately modifying the planned movements while climbing referred to the climber's modifications as he attempted to improve his climbing fluency. These modifications involved either hand chaining or hand-foot chaining. The general dimension Adjusting foot chaining while climbing referred to the climber's actions linked to the hold-by-hold improvisation of the feet, meaning that he had not planned a detailed chaining for his feet during the preview as he expected that the feet would follow the

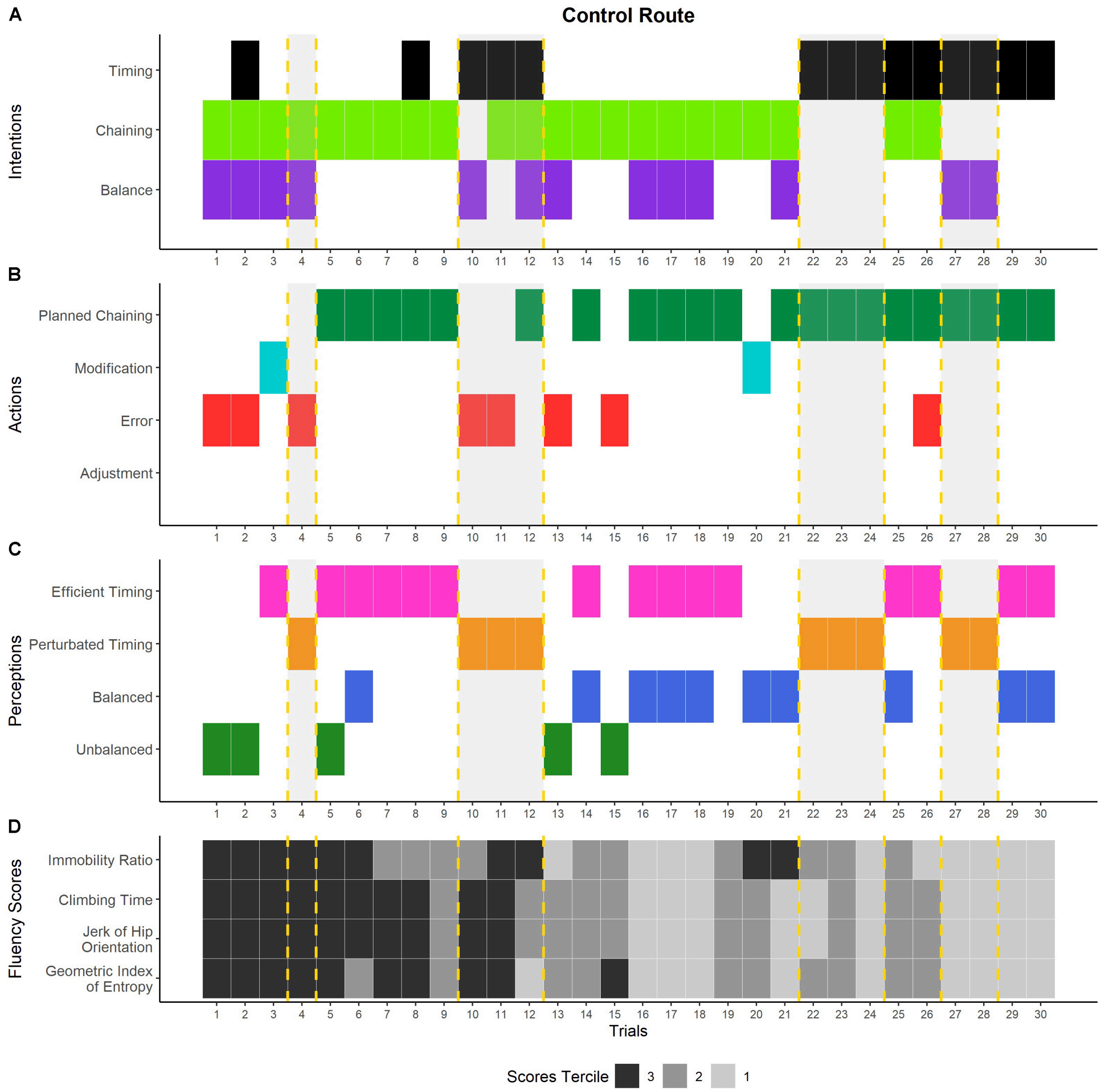

FIGURE 4 | Dynamics of the climber's experience and performances on the control route. Panels **A–C** show the temporal organization of the general dimensions of the different components of experience detected during the interviews. Panel **A** shows the general dimensions of the climber's intentions: Improving the timing of the climb (black), ensuring the correct execution of movement chaining (light green), and seeking and maintaining balance while climbing (purple). The climber's actions are shown in panel **B:** carrying out the planned chaining (dark green), deliberately modifying the planned movements while climbing (light blue), making errors while climbing (red), and adjusting the foot chaining while climbing (gold). Panel **C** shows the general dimensions of the climber's perceptions: sensation of efficient timing (pink), sensation of perturbed timing (orange), sensation of being balanced (dark blue), and sensation of being unbalanced (green). Panel **D** shows the score terciles for each fluency indicator. The climbing performance is expressed in the terciles: tercile 3 (in black) refers to his poorest performances, tercile 2 (in dark gray) refers to his intermediate performances, and tercile 1 (in light gray) refers to his best performances. The vertical dashed lines delimit the crucial episodes in the climber's experience.

hands. As a consequence, he systematically looked at his foot placement when moving from one hold to another, leading to improvisations, hesitations, or careful observations of the holds before using them.

Perceptions

The results of the thematic analysis of the climber's perceptions revealed four general dimensions (**Figure 3**): (i) Sensation of being balanced, (ii) Sensation of being unbalanced balance, (iii) Sensation of efficient climbing timing, and (iv) Sensation of perturbed climbing timing. These general dimensions encompassed the climber's meaningful perceptions during the climbs; it is important to note that for a given climb, several perceptions may have emerged simultaneously (e.g., efficient climbing timing and balance). The general dimension Sensation of being balanced referred to the climber's positive perceptions of

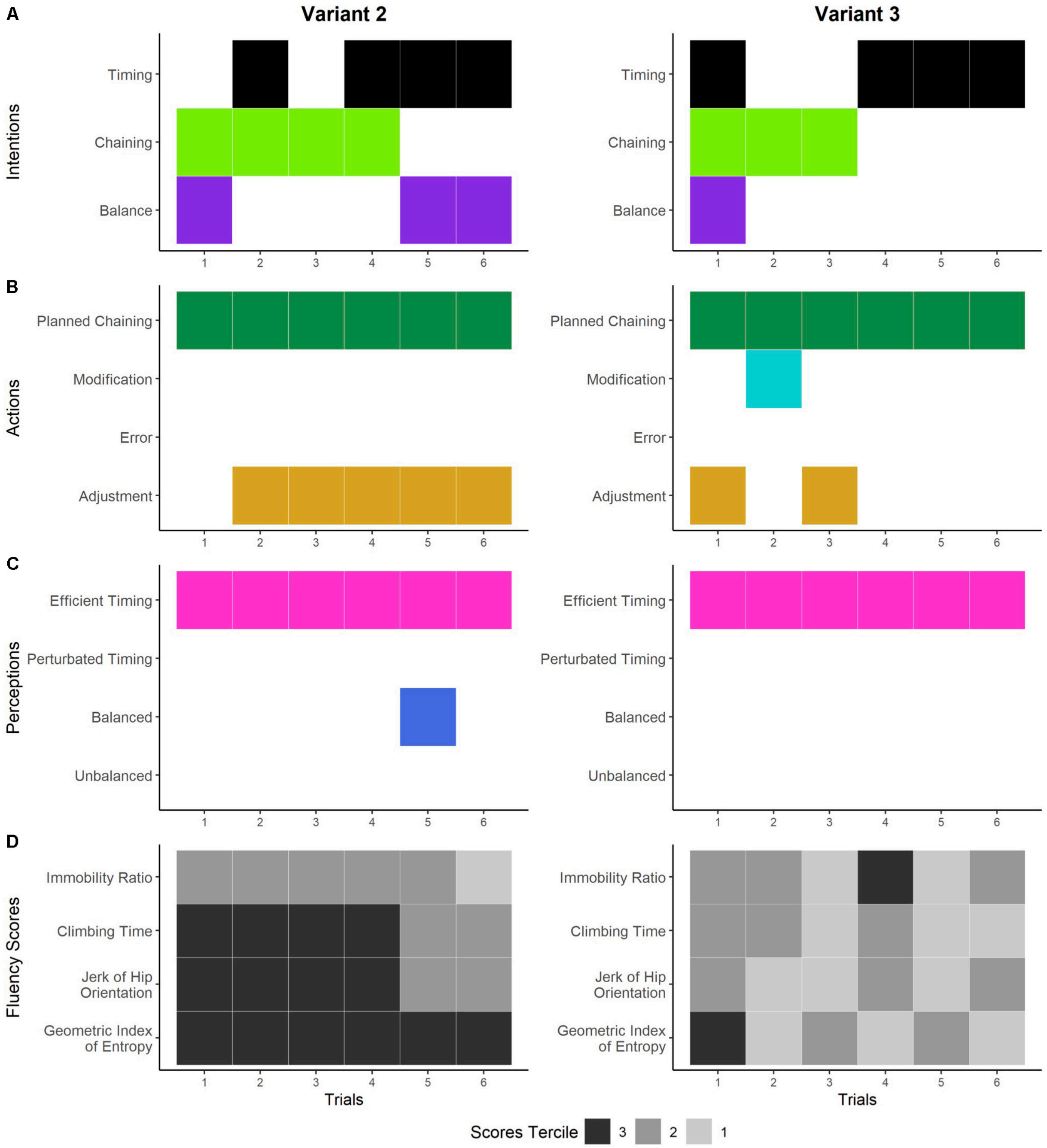

FIGURE 5 | Dynamics of the climber's experience and performances on variants 2 and 3. Panels **A–C** show the temporal organization of the general dimensions of the different components of experience detected during the interviews. Panel **A** shows the general dimensions of the climber's intentions: improving the timing of the climb (black), ensuring the correct execution of movement chaining (light green), and seeking and maintaining balance while climbing (purple). The climber's actions are shown in panel **B:** Carrying out the planned chaining (dark green), deliberately modifying the planned movements while climbing (light blue), making errors while climbing (red), and adjusting the foot chaining while climbing (gold). Panel **C** shows the general dimensions of the climber's perceptions: sensation of efficient timing (pink), sensation of perturbed timing (orange), sensation of being balanced (dark blue), and sensation of being unbalanced (green). Panel **D** shows the score terciles for each fluency indicator. The climbing performance is expressed in the terciles: tercile 3 (in black) refers to his poorest performances, tercile 2 (in dark gray) refers to his intermediate performances, and tercile 1 (in light gray) refers to his best performances.

balance, such as the sensation that the plexus was aligned along the vertical axis or stability via the feet. The general dimension Sensation of being unbalanced referred to the climber's negative perceptions of losing balance, such as uncomfortable, unstable, and unsafe positions of the body or feet, which perturbed the perceived fluency. The general dimension Sensation of efficient

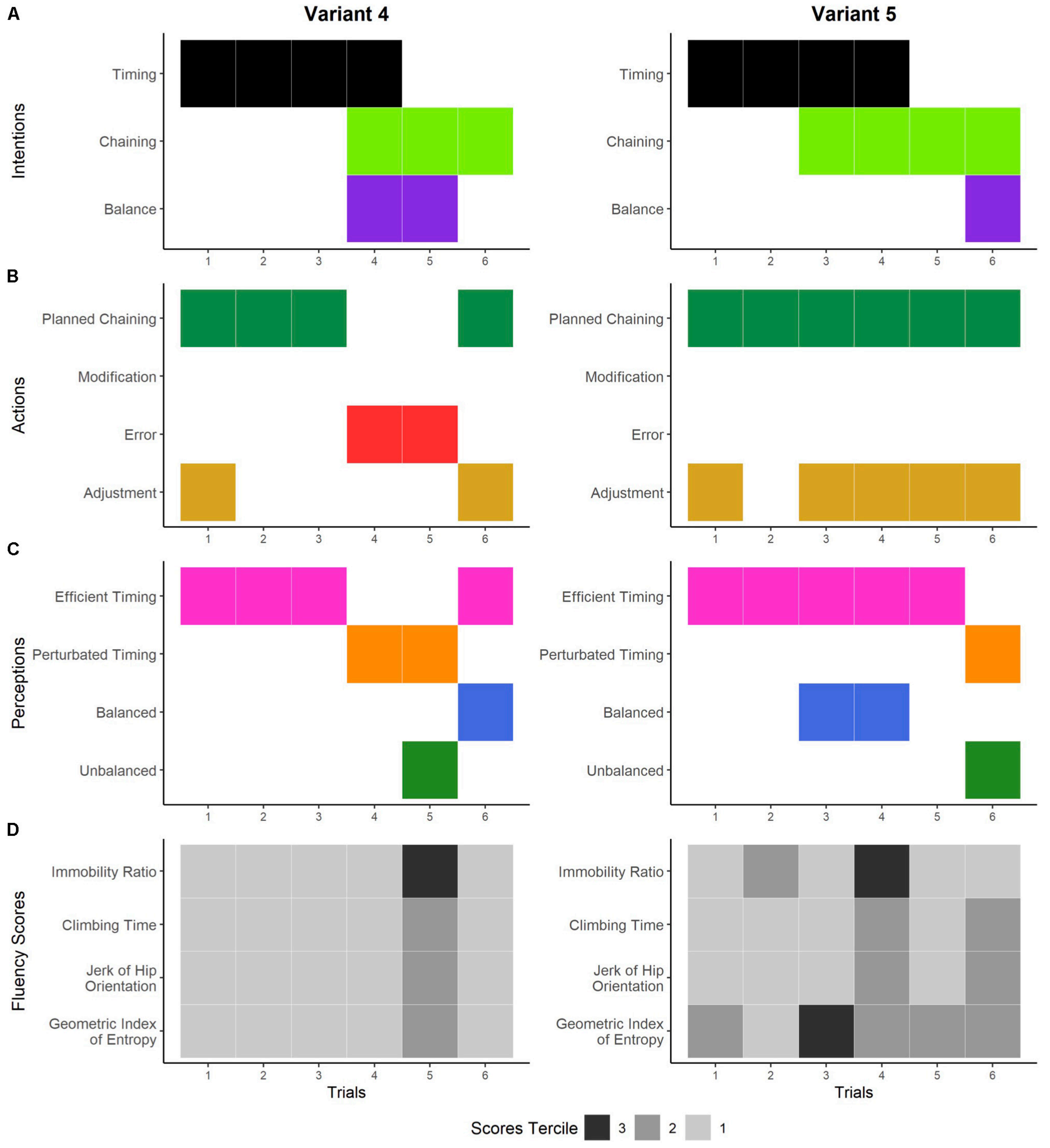

FIGURE 6 | Dynamics of the climber's experience and performances on variants 4 and 5. Panels **A–C** show the temporal organization of the general dimensions of the different components of experience detected during the interviews. Panel **A** shows the general dimensions of the climber's intentions: improving the timing of the climb (black), ensuring the correct execution of movement chaining (light green), and seeking and maintaining balance while climbing (purple). The climber's actions are shown in panel **B:** carrying out the planned chaining (dark green), deliberately modifying the planned movements while climbing (light blue), making errors while climbing (red), and adjusting the foot chaining while climbing (gold). Panel **C** shows the general dimensions of the climber's perceptions: sensation of efficient timing (pink), sensation of perturbed timing (orange), sensation of being balanced (dark blue), and sensation of being unbalanced (green). Panel **D** shows the score terciles for each fluency indicator. The climbing performance is expressed in the terciles: tercile 3 (in black) refers to his poorest performances, tercile 2 (in dark gray) refers to his intermediate performances, and tercile 1 (in light gray) refers to his best performances.

climbing timing referred to the climber's positive and efficient perceptions of the climbing timing and contributed to the perception of good climbing fluency. This efficient timing was perceived at the level of the whole body displacement (i.e., no stops or saccades, sensations of being in constant movement, sensation of speed), the hand chaining (i.e., sensations of

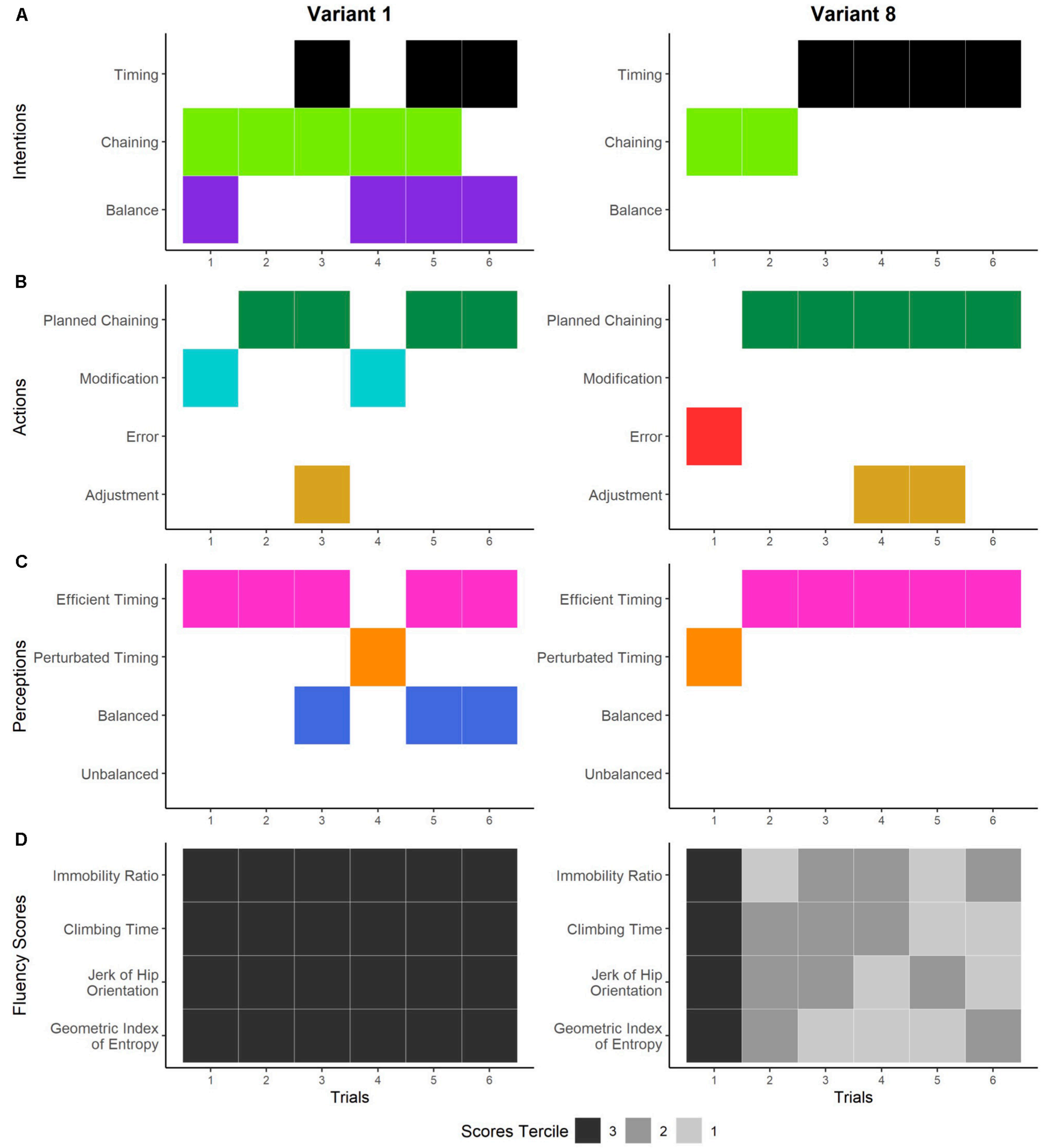

FIGURE 7 | Dynamics of the climber's experience and performances on variants 1 and 8. Panels **A–C** show the temporal organization of the general dimensions of the different components of experience detected during the interviews. Panel **A** shows the general dimensions of the climber's intentions: seeking and maintaining balance while climbing (purple), ensuring the correct execution of movement chaining (light green), and improving the timing of the climb (black). The climber's actions are reported in panel **B:** adjusting the foot chaining while climbing (gold), making errors while climbing (red), deliberately modifying the planned movements while climbing (light blue), and carrying out the planned chaining (dark green). Panel **C** shows the general dimensions of the climber's perceptions: sensation of being balanced (dark blue), sensations of being unbalanced (green), sensations of efficient timing (pink), and sensations of perturbed timing (orange). Panel **D** shows the score terciles for each fluency indicator. The climbing performance is expressed in the terciles: tercile 3 (in black) refers to his poorest performances, tercile 2 (in dark gray) refers to his intermediate performances, and tercile 1 (in light gray) refers to his best performances.

regular pace and dynamic tempo), or the hand-foot chaining (i.e., sensation of climbing a ladder, efficient synchronization, and tempo). The general dimension Sensation of perturbed climbing timing referred to the climber's negative perceptions of the timing, which altered the perceived climbing fluency. This perturbed timing was perceived either through perturbations

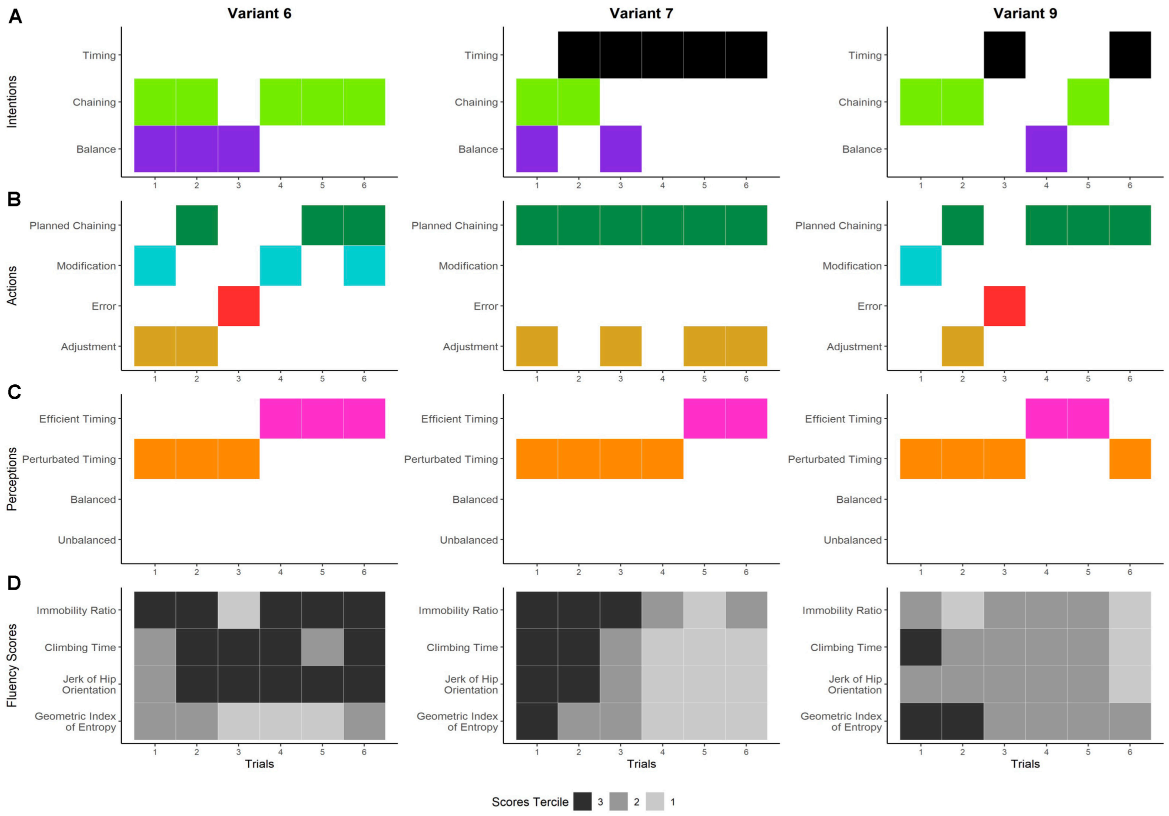

FIGURE 8 | Dynamics of the climber's experience and performances on variants 6, 7, and 9. Panels **A–C** show the temporal organization of the general dimensions of the components of experience detected during the interviews. Panel **A** shows the general dimensions of the climber's intentions: seeking and maintaining balance while climbing (purple), ensuring the correct execution of movement chaining (light green), and improving the timing of the climb (black). The climber's actions are shown in panel **B:** Adjusting the foot chaining while climbing (gold), making errors while climbing (red), deliberately modifying the planned movements while climbing (light blue), and carrying out the planned chaining (dark green). Panel **C** shows the general dimensions of the climber's perceptions: sensation of being balanced (dark blue), sensation of being unbalanced (green), sensation of efficient timing (pink), and sensation of perturbed timing (orange). Panel **D** shows the score terciles for each fluency indicator. The climbing performance is expressed in the terciles: tercile 3 (in black) refers to his poorest performances, tercile 2 (in dark gray) refers to his intermediate performances, and tercile 1 (in light gray) refers to his best performances.

in the climbing fluency (i.e., stops, saccades, immobility, and perturbation in the chaining) or the sensation of inefficient slowness (i.e., sensations of climbing slowly and spending too much time on the holds).

The identification of these general dimensions, which made up the climber's own world in his definition of enacted fluency, indicated that his definition of fluency was mainly linked to the notion of timing. Indeed, for intentions, 44 occurrences referred to improvements in timing, and for perceptions, 77 occurrences referred to the sensation of efficient or disturbed timing. This salience of timing was mainly actualized through the execution of a planned chaining (64 occurrences). In other words, according to the climber, climbing fluently means climbing with efficient timing - that is, no saccades, no stops, and being in constant movement.

Dynamics of These Experiences in the Unchanged Environment

As we detail below, the analysis of the dynamics of the climber's definition of his enacted fluency revealed the importance of climbing with efficient timing. We therefore focused on episodes (i.e., one trial or a succession of trials) where perturbations in the timing emerged in the climber's perceptions (**Figure 4C**). We successively present: (i) the dynamics of the climber's lived experience in the unchanged environment in association with the evolution of the four indicators of fluency (i.e., CT, percentage of immobility, GIE, and jerk) and (ii) the crucial episodes in which the timing of the climb was lived as perturbed.

Dynamics of the Climber's Lived Experience on the CR

As shown in **Figure 4A**, in the unchanged environment (i.e., the CR), the general depiction of the dynamics of the intentions showed that the climber was mainly concerned with ensuring the correct execution of chaining (trials 1–21). It should be noted that trials 1–6 were characterized by the second-order theme Correctly performing the planned hand chaining before moving to the second-order theme, Correctly performing the planned hand-foot chaining (trials 7–21). Then a switch occurred in trial 22, where the intention to improve the climbing timing

TABLE 2 | The interval values identifying the terciles for the geometric index of entropy (GIE), jerk, immobility ratio (IR, in percentage), and climbing time (CT, in seconds).

Tercile	Trials (*N*)	GIE	Jerk	IR (%)	CT (s)
Control route					
1	10	0.55–0.72	10.28–11.48	6.99–16.64	8.86–11.17
2	10	0.72–0.85	11.48–12.34	16.64–23.72	11.17–13.56
3	10	0.85–1.40	12.34–16.00	23.72–42.42	13.56–38.05
Variants					
1	18	0.58–0.67	10.53–11.37	7.17–15.09	8.79–10.72
2	18	0.67–0.78	11.37–12.19	15.09–20.10	10.72–13.11
3	18	0.78–1.25	12.19–14.98	20.10–42.63	13.11–29.18

All interval values are presented for the control route and the nine variants (all together). For tercile 1, the minimal values correspond to his absolute best scores, while the maximal values of tercile 3 correspond to his absolute worst scores.

for the hand chaining emerged as salient, as characterized by the second-order theme Pacing the climb with dynamic hand chaining. Regarding his actions, while he mainly carried out his planned chaining (**Figure 4B**), he made errors at the beginning (trials 1, 2, and 4) and in trials 10, 11, 13, 15, and 26, which were accompanied by deliberate modifications in trials 3 and 20. The general dynamics of the perceptions show an entanglement of the sensations linked to balance and timing, made up of frequent switches from "positive" elements (i.e., balance and efficient timing) to "negative" elements (i.e., losses of balance and perturbed timing) and inversely (**Figure 4C**). We can observe that the issues linked to losses of balance (trials 1, 2, 13, and 15) were associated were errors in chaining, which gave rise to intentions about maintaining balance. The modalities through which perturbed timing was perceived changed over time: from sensations of disruptions in the climbing fluency because of stops and saccades (trials 4 and 10–12) to sensations of inefficient slowness of the hand chaining and the time spent on the holds (trials 22–24 and 27, 28). Similarly, the modalities through which efficient timing was perceived moved from the absence of stops and saccades (trials 5–9) toward sensations of efficient hand-foot synchronization (trials 16–19) and rhythm in the chaining (trials 25, 26, 29, and 30). Finally, the dynamics of his evolving fluency scores showed a global non-linear progression from performances in the third tercile (trials 1–5) to the second tercile, and then the first tercile in trials 16–19 and trials 27–30 (**Figure 4D**).

The Crucial Episodes of Perturbed Timing

The dynamics of the general dimensions of the climber's experience during the 30 trials on the CR revealed four crucial episodes. These episodes were qualified as crucial because they were characterized by disruptions in the climbing timing, which were characterized as follows:

Episode 1, trial 4: an unplanned hand-crossing that disrupted the timing

Prior to this episode, the first two trials were characterized by errors in hand chaining during which the climber felt losses of balance before making a modification in trial 3. In trial 4, the climber had hand-focus intentions in the sense that he sought to perform correct hand chaining from the bottom to the top in order to avoid errors and losses of balance. However, after a fluent first section, he made an error with his hands in the middle of the route (i.e., he crossed his hands) and felt immobile. He characterized this error as disrupting the promising fluency he had felt at the start and was disappointed because he could not actualize his entire plan for the hand chaining. The error made in this climb was crucial for the climber as he explicitly built the knowledge that hand crossing was a threat to fluency and had to be avoided in the following climbs, as illustrated by the following excerpt from verbalizations on trial 4:

> Climber: [points to the moment in the video where he found himself with crossed arms on two holds and the end of the route] "And here, I had expected to do a hand repetition [two successive handholds with the same hand] but at the end I was doing just anything, kind of unthinkingly like a robot.
> Researcher: And suddenly, there you cross your arms.
> Climber: Yes. That's the mechanical side, I crossed them and that was a huge mistake. That brought my whole body to a standstill.
> Researcher: So there, how were you feeling about the fluency at that point?
> Climber: I was feeling fluent all along the route but at that moment where I made the mistake with my hand, I thought oh great now it's over. There I knew that it wasn't good . . . Having your arms crossed doesn't feel good, but more than anything, it's not at all practical . . . it gets really jerky. At least it helped me to know how to do things better the next time, to make up for mistakes like that in the next trials and avoid crossing my hands.

This episode was confirmed by poor fluency scores, as all indicators were in the third tercile.

Episode 2, trials 10–12: the feet that slow down the ascension

This episode characterized the switch from hand-focused intentions to hand-foot focused intentions, meaning that the climber was no longer exclusively concerned about correct hand chaining but was trying to improve his fluency by integrating the feet as part of the whole chaining. This switch to hand-foot chaining had been successfully initiated in trials 7–9 (he felt like he was climbing on a ladder and the scores moved to the second tercile in trial 9). However, during this episode, while he attempted to keep the same hand-foot chaining, he made an error in the hand chaining in trial 10 and an error in the foot chaining in trial 11 despite his attempt to stick to his planned hand-foot chaining: "When I finished it, I thought that my fluency on that route was zero because there were moments where I stopped, small hesitations with my feet. In any case, I thought it was no good. So it showed me where I needed to be careful in the next trials" (trial 10). These errors led to sensations of lacking rhythm and being stuck on the holds, which negatively impacted his assessment of his climbing fluency: "I don't feel like I was very successful on that route . . . I don't know, there was no flow, I felt slow" (trial 11). This negative perception of fluency was confirmed by the scores (all are in the third tercile, except for the IR which was in tercile 2 in trial 10). In trial 12, he recited his planned hand-foot chaining but still had the sensations of being slow and spending too much time on the holds. In spite of these sensations, the scores for the GIE, jerk, and CT improved.

Episode 3, trials 22–24: the sensation of inefficient slowness
In this episode, the climber was no longer concerned about his hand-foot chaining but instead he sought to improve his climbing timing by pacing his climb with dynamic hand chaining; "I'm thinking that I have to be more dynamic so I don't get stuck on the handholds, I have to move from one to another. I rehearse with my hands, I know the chaining by heart, I don't want to bother with the feet because I have the impression that that had an impact, thinking about my feet, and so I rehearse with my hands so I don't get upset . . . So I want to be hyper-dynamic, just with my hands" (trial 24). During the climbs, the climber recited his well-known hand chaining without errors or modifications but had the sensation of climbing slowly (trials 22 and 23) and spending too much time on the holds, and so he assessed his fluency as poor: "My whole body is slow, I can't keep up a steady rhythm, there's always a moment of slowdown, of kind of floating and so it's not fluent . . . and every time it stops because I look down to make sure I don't mess up with my feet. I wanted to be dynamic but I wasn't." Although he perceived his fluency as poor in this episode, these negative perceptions were contrasted by the scores, which moved to terciles 2 and 1, especially for trial 24 (all indicators reached tercile 1).

Episode 4, trials 27–28: saccades and compensation
In this episode, the climber knew his hand chaining by heart (he was no longer concerned with the feet chaining, he just expected them to "follow" the pace imposed by his hands), and sought to improve his climbing fluency by pacing his climb with dynamic hand chaining. However, during trial 27, one of his feet slipped from a hold and he had to compensate by pulling with his arms to restore his position and finish his climb. At this moment, the climber felt a saccade that perturbed his fluency but was relieved that he had managed to maintain fluency with his hands: "My foot slipped on the hold just when I pushed on it . . . I was so mad! I fixed it by pulling with my arms . . . the fluency wasn't too bad, except for the foot that slipped and caused me to jerk." In trial 28, he had the same intention of putting dynamism in the hand chaining and recited his planned chaining, but then felt that he was slow when grasping the holds, as he felt a small saccade before each handhold: "Fluency is not really that, there's a little jerk of the hands when I grab the holds, my hands slow on each hold . . . ." This episode was characterized by good fluency scores in tercile 1, in contrast to the climber's experience.

Dynamics of the Climber's Enacted Fluency in the Novel Environments

The analysis of the timing perturbations that were meaningful to the climber enabled us to identify four ways of experiencing novelty: novelty without perturbation (variants 2 and 3), novelty without immediate perturbation (variants 4 and 5), novelty as a source of punctual perturbation (variants 1 and 8), and novelty as a source of recurrent perturbation (variants 6, 7, and 9).

Novelty Without Perturbation

This way of experiencing novelty was identified in variants 2 and 3 (**Figure 5**). In the first trial on variant 2, the climber sought to maintain his balance and chain his hands correctly (**Figure 5A**, left). He carried out his chaining while simultaneously looking at the foot placement (**Figure 5B**, left). He had positive perceptions of ease and efficient timing (i.e., no stops, no saccades, and constant movement of the body) (**Figure 5C**, left) and was pleased. In the following climbs, he no longer focused on the correctness of his chaining but instead on balance and improving his timing by putting dynamism into his hand routine, as illustrated by the following excerpt: "I know the chaining now, so what's important is to make it dynamic . . . so it has to flow, no more losing time" (Variant 2, trial 2). While performing his routine in trials 2–6, he also felt an efficient timing (i.e., no stops, no saccades, and constant movement of the body). His fluency scores showed an improvement in the temporal indicators (i.e., from tercile 2 to 1 for the IR, from tercile 3 to 2 for the CT and the jerk) while the spatial indicator (i.e., the GIE) remained in tercile 3 for all the climbs (**Figure 5D**, left).

In the first trial on variant 3, the climber's intentions were also linked to climbing rapidly while maintaining balance and correctly chaining the hands (**Figure 5**, right). He carried out his hand plan and adjusted his foot placement at the same time (**Figure 5B**, right). He felt sensations of climbing fast with no stops in his climbing pace (**Figure 5C**, right). In trial 2, while he was focused on maintaining the correct execution of hand chaining, he modified the foot chaining and felt a better pace. He validated this change for the subsequent trials by integrating his feet into the planned chaining. He felt an efficient hand-foot synchronization that he expressed as "climbing like on a ladder." His scores were mainly in terciles 1 and 2, and in tercile 3 for the GIE in trial 1 and immobility in trial 4. In sum, he discovered that he could use his feet to improve fluency by synchronizing their movements with the hand chaining (i.e., he felt a better climbing pace that he described as "climbing like on a ladder") and showed a tendency to a convergence between his perceived fluency and the scores (**Figure 5D**, right).

The climber's way of acting in these environments – where he experienced no perturbation of the timing of his climbs –

consisted of elaborating a chaining plan and ensuring its correct execution to guarantee efficient timing. The attempts to carry out his plans were not always accompanied by high fluency scores.

Novelty With Delayed Perturbations

This way of experiencing novelty was identified in variants 4 and 5 (**Figure 6**). During the first three trials on variant 4, the climber sought to climb this route like a ladder by pacing his planned hand-foot chaining to improve his timing (**Figure 6A**, left). He recognized that the spatial layout of the holds would let him climb the route "like a ladder" and expressed his intentions to do so: "I'm thinking to do right arm, left arm, right arm, left arm so it seems like a ladder (he rhythmically mimes the left–right alternations), I'm looking for the rungs [of the ladder]. So finally, I try to climb like I'm on a ladder" (variant 4, trial 1). He carried out his plan and felt an efficient hand-foot timing (**Figures 6B,C**, left). He started trial 4 with the intention of maintaining his balance, ensuring the correct execution of his planned hand-foot chaining, and improving the timing through synchronized hand-foot movements. He nevertheless made an error in the foot chaining and slipped, causing a perturbation to his perceived hand-foot timing. The same scenario occurred in trial 5, where he made an error in the hand chaining, which unbalanced him and also perturbed his hand-foot timing. After trials 4 and 5, he concluded that integrating the feet in the elaboration of a chaining was not efficient for fluency because it increased the possibility of avoidable errors and stops. Therefore, in trial 6, he decided to focus exclusively on his hand chaining, which he carried out while adjusting the foot chaining at the same time, as he had no prior plans for them. By doing so, he stopped less often and again felt efficient timing. All his scores were in tercile 1, except for trial 5, in which the IR was in tercile 3 and the CT, jerk, and GIE were in tercile 2 (**Figure 6D**, left).

In the first five trials on variant 5, he sought the sensations of climbing a ladder by purposely and exclusively focusing on the timing of his hands (**Figure 6A**, right). He carried out the planned hand chaining and adjusted his feet (**Figure 6B**, right). He felt a regular rhythm in his movements as well as an efficient hand-foot alternation and balance (**Figure 6C**, right). In trial 6, he also carried out the hand chaining while adjusting the feet at the same time but he felt saccades that negatively impacted his perception of fluency. His scores were mainly in terciles 1 and 2 and the GIE of trial 4 and the IR of trial 5 were in tercile 3 (**Figure 6D**, right).

In sum, for each first trial on variants 4 and 5, the climber had direct intentions to improve the timing of his climbs. The ladder metaphor was useful for anticipating the hand-foot chaining and timing in the aim of improving climbing fluency, but it also led to errors and balance losses that perturbed the timing. As a consequence, the climber decided to focus exclusively on his hands, and he carried out the planned-on chaining while adjusting the foot chaining at the same time, as there was no prior plan for them. Overall, the way of metaphorically living his climb as he looked for efficient timing was confirmed by high fluency scores, and the perceived errors and perturbations were confirmed by poorer scores.

Novelty as a Source of Punctual Perturbation

This way of experiencing novelty was identified on variants 1 and 8 (**Figure 7**). In the first trial on variant 1, the climber sought to maintain his balance and correctly chain his hands (**Figure 7A**, left). He deliberately modified this chaining while climbing and had the sensation that his whole body was in constant movement (**Figures 7B,C**, left). In trial 2, he carried out the hand chaining, including the modification he had made in the previous climb, and perceived his timing as efficient. In trial 3, he sought to climb faster to improve his fluency. He executed his hand chaining and adjusted his feet at the same time. He again had the sensation of efficient timing (i.e., no stops, saccades, or hesitations). In trial 4, he sought to reproduce the same climb but he modified his hand chaining and felt stops that perturbed his timing. In trial 5, he carried out his initial hand chaining and felt speed and balance. In trial 6, he was no longer concerned with sticking to his plan for chaining but rather sought sensations of balance and speed. He executed his plan and had good sensations of timing and balance. In sum, while he progressively constructed his chaining with modifications throughout the trials, he felt a progressive improvement in his fluency (i.e., body in constant movement, speed, and balance). Despite his promising sensations of timing, his scores were all in tercile 3 for each trial (**Figure 7D**, left).

In the first trial on variant 8, he made errors in hand chaining (**Figure 7B**, right). He felt that his chaining was completely perturbed and had the sensation of being stuck on the route, which perturbed his timing (**Figure 7C**, right).

> Researcher [at the beginning of the climb]: So there you take off, you do left hand, right hand.
> Climber: There, I put out my right hand, the worst thing to do. So suddenly I didn't know what to do to untangle myself so I started thinking . . . I said, oh boy this is going to be complicated, what am I going to do . . . Suddenly, I sent my right hand up somehow . . . but right away, it missed and it was a mess and I had no backup plan in case it didn't work . . . so fluency level: zero . . . everything I had planned to do was completely perturbed, a complete failure because then I started to hesitate and I just got blocked. So for the next climb, I thought just put your left hand there at the beginning and after that, it'll be easy. The key is the start (variant 8, trial 1).

This perturbation was confirmed by the scores, which were all in tercile 3 in the first trial (**Figure 7D**, right). In the following five trials, he sought to avoid the error in chaining and put dynamism in his hand chaining. He recited his planned chaining and felt he was dynamic, with an efficient timing and fluency. Congruently, his scores were in terciles 1 and 2 in the other trials (**Figure 7D**, right).

In sum, in these two variants, the climber constructed his chaining through punctual errors and modifications, which helped to build, improve, and optimize his chaining until he could look for efficient timing. This search for timing efficiency was either never confirmed by high scores (cf. variant 1) or followed a tendency to progression (cf. variant 8).

Novelty as a Source of Recurrent Perturbation

This way of experiencing novelty was identified on variants 6, 7, and 9 (**Figure 8**). On variant 6, the climber reported that the global impression that his climb was not well integrated (i.e., sensations of spending too much time on the holds and inefficient slowness). In trial 1, he modified his planned hand chaining while climbing and had the sensations of spending too much time on the holds and inefficient slowness (**Figures 8B,C**, upper left). While he carried out his plan in trial 2, he still had the same sensations that perturbed his timing. In trial 3, he made an error in the hand chaining that made him feel that he was moving slowly and taking too long. In trial 4, he modified his chaining and felt better sensations of timing (i.e., no stops and constant rhythm). In trials 5 and 6, he recited the modified plan and again had positive sensations of efficient timing. While he perceived progressive improvements in his fluency from trials 1 to 3 and 4 to 6, his scores did not reflect this as most of his temporal scores were in tercile 3 (except for the IR in trial 3, which was in tercile 1) and the spatial indicator (GIE) was between terciles 1 and 2 (**Figure 8D**, upper left).

On variant 7, although he recited his planned hand chaining in all the trials (**Figure 8B**, upper right), he had several hesitations with his foot placement from trials 1 to 4 that perturbed his timing in the sense that he felt his feet were "braking" the hand pace (i.e., he had the sensation of spending a long time finding footholds, slowness, and even some stops):

> Climber: I was hesitating a lot with my feet, I had to really look for the footholds. Suddenly I was blocked with my hands.
> Researcher: So if I understand you, chaining the hands was fine but the feet were a problem. When this happens, how do you feel the fluency?
> Climber: Well, I have the sensation that time has slowed down. I'm spending time on the holds, so I don't feel fluent at all. My feet really slowed me down.

Hence, he intended to improve his timing with dynamic hand chaining (**Figure 8A**, upper right). In trials 5 and 6, he also recited the chaining while also adjusting his feet and felt more dynamic. His scores progressively improved from tercile 3 to tercile 1 throughout the trials (**Figure 8D**, upper right).

In the first trial on variant 9, the climber created a new chaining, which he then modified while climbing (**Figure 8B**, lower left). While making this modification, he felt stops and small hesitations (**Figure 8C**, lower left). In trial 2, he focused on reproducing the hand chaining. He recited it while looking at his feet and he also felt his feet were slow. In trial 3, he sought to climb dynamically but he made an error with his hands, his feet slipped, and he felt bad sensations about the timing. In trials 4 and 5, he carried out the planned hand chaining and had better sensations of pace. In trial 6, he sought speed in his hand chaining; while he recited the chaining, he felt slow and jerky. His scores were mainly in tercile 2, except for the CT in trial 1 and the GIE in trials 1 and 2, which were in tercile 3 (**Figure 8D**, lower left).

In sum, on these three variants, the climber constructed his chaining through errors and modifications but he never managed to feel efficient timing. While the fluency scores were overall poor, in one case the scores matched the sensation of inefficient timing (cf. variant 6), and in another case (variants 7 and 9), the improvement in the fluency scores was not perceived as such.

DISCUSSION

The aim of this case study was to analyze the dynamics of a novice climber's lived experience and performances during a 10-session training protocol of different climbing tasks. He was confronted with both unchanged and novel routes and was instructed to climb as fluently as possible. Our analysis methodology focused on integrating the climber's experience with his "objectivized" progression, which enabled us to obtain a detailed depiction of what was meaningful for him during the learning protocol. In other words, we sought to characterize the climber–environment coupling from what was meaningful for him. This methodology enabled us to highlight what we termed a phenomenological synthesis, which refers to the way an actor deals with the complexity of the interaction between his activity and the learning environment.

Our results are summarized around the following points: (i) the climber's construction of significations in terms of his intentions, actions, and perceptions that defined how he enacted his fluency in timing; (ii) the non-linear progression of his performance in the unchanged environment and the crucial episodes in his experience; (iii) the four ways of experiencing the novel environments that were identified: novelty without perturbation, novelty with delayed perturbation, novelty as a source of punctual perturbation, and novelty as a source of recurrent perturbation); and (iv) the climber's perception of fluency, which was not systemically matched by his performance scores. Our discussion focuses on the following points: (i) the enacted fluency as a phenomenological synthesis of the climbing activity, (ii) the emergence and definition of the phenomenological synthesis, and (iii) the dynamic property of the phenomenological synthesis.

The Enacted Fluency as a Phenomenological Synthesis of the Climbing Activity

The enactive paradigm conceives the relation between an actor and the environment as a structural and dynamic coupling (Varela et al., 1991). This means that the climber considered the complexity of the significations he was building through his intentions, actions, and perceptions. He defined, from his point of view, the learning environment: the material and spatial layout of the climbing routes, the task instructions (i.e., to climb as fluently as possible), and the fluency scores. We suggest that the climber summarized this complexity through a phenomenological synthesis. This synthesis expressed his specification of his own world and it is probable that another climber would have had another phenomenological synthesis.

To face the task requirements in the two types of environments (unchanged and novel routes), the climber created his own definition of fluency, which was expressed through the presence/absence of balance, stops, saccades, execution of the planned hand chaining or hand-foot chaining, and climbing timing. His definition of fluency was specifically highlighted by the results of our thematic analysis (**Figures 1–3**), which showed that he expressed his concern about improving the timing of his climbs by carrying out the movements that he assessed as efficient. The enacted fluency was embedded in the climber's experience as intentionality (i.e., expectations, concerns, and goals), embodiment (actualization through his meaningful actions, multi-modal perceptions), and sense-making (i.e., the construction of meaning and the knowledge built from the interactions with the learning situations). On the basis of these results, we discuss the emergence and definition of this phenomenological synthesis and its dynamic property. Indeed, as we will detail below, this phenomenological synthesis enabled the climber to assess, adjust, explore, and create chaining, which participated in re-defining this synthesis.

Emergence and Definition of the Phenomenological Synthesis

Our results show that the emergence and definition of the phenomenological synthesis during the first interaction with a learning environment is stimulated either by links to past experiences or by the actor's perceptions and appropriation of the learning environment. In our study, the climber referred to past experiences that he assessed as similar in this environment, giving rise to what we qualify as the effect of metaphor (i.e., climbing a ladder). This effect characterized his coupling with the environment and the use of pre-existing coordination (i.e., the movement of climbing a ladder), which refers to a pre-built chaining. For example, on variants 4 and 5 (**Figure 6**), the climber directly engaged with these novel environments with the intention to efficiently synchronize his hands and feet because the spatial layout of the holds suggested that he perform his chaining as if he were on a ladder. This metaphorical effect might lead to a satisfaction or new perturbations, which would participate in re-defining the phenomenological synthesis. Although the metaphorical effect enabled the climber to engage directly with expectations linked to efficient fluency, it did not preclude the emergence of errors. Indeed, in trial 4 on variant 4, he made an error in foot chaining, which had repercussions for the hand chaining and consequently he assessed his fluency negatively, which was confirmed by the scores.

In other cases, the recognition of similarities with past experiences did not emerge from the coupling with the environment. Rather, it was the significations built by the climber at that moment that participated in defining his phenomenological synthesis to act in a novel environment. For example, the first few times the climber climbed the CR (i.e., a new route), he made errors in trials 1 and 2, made a modification in trial 3, and made another error in trial 4, before carrying out his planned chaining from trials 5 to 9 (**Figure 4**). However, as observed on both CR and the variants, the execution of his plans did not prevent him from making errors or modifications, which generated further modifications and transformations of the phenomenological synthesis. Our results for all the variants showed that meaningful perturbations emerged at different moments in the task (i.e., delayed and no perturbation) in different forms (i.e., punctual or recurrent perturbation), highlighting the unpredictable, non-prescriptive, and autonomous properties of activity. In what follows, we will consider the extent to which the phenomenological synthesis was under perpetual modification, thus dynamically rebuilding the climber's own world.

The Dynamic Property of the Phenomenological Synthesis

Our results reveal the non-linearity of the climber's lived experiences on both the CR and the variants. This non-linearity was linked to the dynamic property of the phenomenological synthesis, as the performance of a memorized chaining did not preclude the emergence of errors (i.e., described as such by the climber) that perturbed this synthesis, causing him to lose his balance, stop his progress, and display jerky behavior, thereby perturbing his timing. These perturbations led to adjustments in the phenomenological synthesis for the subsequent trials. For example, the error he made during episode 1 on the CR (i.e., he crossed his hands and was blocked in his ascension) prompted him to avoid crossing his hands in the following climbs and hence modify his movement sequence. In trial 5 on variant 4, he made an error in his hand chaining because of inefficient foot placement; this error had direct repercussions on the following trial on variant 4 and in all trials on variant 5, as he decided to abandon the hand-foot synchronization to focus exclusively on his hand chaining (**Figure 6**). Thus, meaningful errors may explain adaptations in learners' intentions and actions, as, for example, in this case: errors prompted the climber to return to previously mastered movements and temporally stop exploring other behaviors.

The dynamic property was identified in our study through two effects: challenge and the refinement in perceptions. Being repeatedly successful in the task (i.e., absence of meaningful perturbation in the enacted fluency) might have prompted the climber to undertake even more challenging actions, which would then encourage the dynamic transformation of the phenomenological synthesis. We have termed this phenomenon the challenge effect. The climber consistently sought to perform the task better, and it is fair to assume that being informed of his scores at the beginning of each session motivated him to try to improve them. After having successfully carried out the same chaining several times, he challenged himself by integrating his feet into the chaining to improve fluency. As shown in **Figure 4**, by adding more body segments to his plans for chaining, he made the task more complex, with the challenge effect characterized by these attempts to synchronize the hands and feet to improve his fluency (see episode 2, trials 10–12). The results show the challenge effect especially on the CR, because the sheer number of climbing repetitions enabled him to (i) turn the execution of successful chaining into a routine and (ii) regularly consult his prior scores, and thus build knowledge about his performance on this route. Relatedly, through the challenge effect, the learner may well have incorporated prompts and task constraints during the repetitions and was thus encouraged to explore new behaviors to meet the expectations even better. However, the challenge effect did not systematically lead to viable modifications in the chaining. Indeed, after the perturbations induced by the challenge, the climber returned to hand chaining, which had previously worked for him. The challenge effect can be linked to the results of studies highlighting intermittent regimes in learning dynamics (Nourrit et al., 2003; Teulier and Delignières, 2007). It can also be assumed that the challenge effect does not emerge for every learner: for example, Orth et al. (2018) observed no progress for some of their participants in a climbing task, as these participants made sure their climbs would be successful by repeating a well-practiced chaining rather than exploring new solutions. The lack of exploration while learning was also reported by Chow et al. (2008): a participant displayed little movement variability and a slower rate of progress. From this perspective, the presence/absence of the challenge effect in the phenomenological data might provide clues to understanding the emergence of new behaviors or the stagnation that comes with repeating the same behaviors.

Throughout the CR trials, the climber's intentions, actions, and perceptions (which constitute the phenomenological synthesis) were transformed in the sense that the timing perturbations were lived differently between the first trials and the last trials, highlighting what we would define as an effect of a refinement in perceptions. Indeed, while the climber did not refer to the time spent grasping each handhold in the first trials on the CR, he perceived and verbalized about these times in the last trials when they seemed to last too long or were hesitant or jerky: he perceived them as sources of perturbation in his fluency. The refinement was observable in crucial episodes: in episode 1 (trial 4), the climber synthesized his perception of fluency through stops and losses of balance that involved his whole body, and in episode 4 (trials 27–28), he synthesized his perception of fluency through sensations of small saccades when the hands were approaching the holds (**Figure 4**). In episode 1 on the CR, the climber perceived the saccades through stops of the whole body and in episode 4 on the CR he perceived the saccades through body parts, mainly the hands before grasping each handhold. On this occasion, the "hesitation" he felt in the hands was lived as a perturbation to fluency. The idea of refining the phenomenological synthesis is congruent with the results of studies of expertise in sports, which have noted that experts have finer sensations than beginners when interacting with artifacts (Gal-Petitfaux et al., 2013; Adé et al., 2017).

From a phenomenological point of view, the dynamics of the climber's live experience revealed that the effect of the refinement in his perceptions was not necessarily reflected in the scores. Indeed, while the dynamics of the lived experience provided insight into some of the perturbations identified at the behavioral level, they also revealed meaningful perturbations that were not reflected in the scores. In this sense, the progressive refinement in perceptions seemed to lead to divergences with the objectivized fluency assessed with stable behavioral indicators (i.e., the CT, the GIE, the IR, and the jerk). As illustrated in **Figure 4**, in episode 1, the poor scores were convergent with the synthesis of the fluency (i.e., stops and loss of balance). In episode 2, this relationship was also convergent, but the scores indicated a tendency toward improvement. In episodes 3 and 4, the scores contrasted with the climber's poor perception of fluency, revealing a divergent relationship between the climber's synthesis and the behavioral assessment. These observations suggest that this progressive divergence between lived experience and performances might have been linked to a certain level of task expertise, in the sense that the climber – even if he lived punctual perturbations – achieved a certain level of fluency as he no longer performed inefficient actions that negatively impacted the scores. This divergence between the dynamics of the phenomenological and behavioral data has been highlighted in other studies (e.g., Gal-Petitfaux et al., 2013; R'Kiouak et al., 2016; Hauw et al., 2017; Seifert et al., 2017) and it provides meaning to the behavioral output in a relation of mutual enrichment (Sève et al., 2013; Depraz et al., 2017; Rochat et al., 2019).

Taken together our findings argue for a phenomenological synthesis between the actor and the environment, in line with theoretical hypotheses about activity in learning (Seifert et al., 2016; Adé et al., 2018; Petiot and Saury, 2019). This synthesis is thus a part of the actor's activity, which constantly participates in re-defining his own world. In this sense and as shown by our results, this phenomenological synthesis is inseparably operatory and dynamic.

CONCLUSION AND FURTHER PERSPECTIVES

Our findings enabled us to conceive and validate a methodology that characterized the dynamics of a learner's lived experiences in relation to the dynamics of his behavior in a learning environment of variable practice. Our results also confirmed and enriched the literature on the enactive conception of learning in physical education and sport (Masciotra et al., 2008; Saury et al., 2013; Hauw, 2018). Indeed, in line with non-linear pedagogies (Chow, 2013), which give much importance to individual pathways in dealing with environmental constraints, the enactive conceptions put the learner's lived experiences as they relate to environmental characteristics at the center of interest. Hence, they have the potential to provide solutions to the issues encountered in studies that use behavioral approaches exclusively. For example, they might provide insight into why some study participants following a given learning protocol do not exhibit the same tendency toward progression as others. Recent studies have underlined that it is important to design learning interventions that help practitioners to take into account learners' lived experiences in learning situations (Durand, 2011; Saury et al., 2013; Adé and Komar, 2018). In this perspective, our study contributes to stimulate the timely reflections that consider the learners' lived experiences as central. As a proposal for further research in sport pedagogy and teaching and in view of our results, we encourage researchers and practitioners to work and reflect on two following ideas. First, to consider learning as a reciprocal transformation: when an actor learns, he/she engages in a process in which he/she transforms himself/herself as well as his/her relationship to the learning environment. Second, to consider learning as a semiosis: each learner – through his/her interaction with the learning environment – brings forth his/her own world and lives his/her own meaningful situation. Hence, learning is enacting significations.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participant provided written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LS designed the study. GH conducted the experiments, and collected and processed the behavioral data. NR and CG collected the phenomenological data. NR, CG, and DA processed the phenomenological data. NR and DA co-wrote the manuscript drafts. CG, GH, DH, PI, and LS reviewed the versions of the manuscript and provided critical feedback.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2020.00249/full#supplementary-material

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