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## Exploring to learn and learning to explore

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2  
3 **Abstract**

4 In respect to ecological psychology processes of attunement and calibration, this  
5 critical review focusses on how exploratory behaviors may contribute to skilled perception  
6 and action, with particular attention to sport. Based on the theoretical insights of Gibson  
7 (1966) and Reed (1996), exploratory and performatory actions have been differentiated in  
8 numerous experiments to study the perception of opportunities of action. The distinction  
9 between exploratory and performatory actions has informed the study of infant behavior in  
10 developmental psychology. In the current article, we highlight limitations with this distinction  
11 in the study of sports performers. We propose that a dynamic view of exploratory behavior  
12 would reveal how individuals develop exploratory activity that generates information about  
13 the fit between environmental properties and action capabilities. In this aim, practitioners  
14 should: (i) give learners the opportunity to safely develop exploratory behaviors even when  
15 they act outside their action boundary; and (ii) guide learners to search for more reliable  
16 information to develop exploratory behaviors that would enhance the transfer of skills to  
17 various performance contexts.

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19 **Keywords:** Skill acquisition, Exploration, Ecological psychology, Perception, Action

## Introduction

Exploration is the continuous and active process through which individuals reveal and pick up information during the control of action (E. J. Gibson 1988; J. J. Gibson 1979/2015). From an ecological psychology perspective, information resides as patterns in ambient energy arrays (e.g., optical, acoustic, mechanical) that specify the state of the relation between the environment and the individual. From this point of view, exploration underpins the relation between information and movement as the energy arrays are structured by the properties of the environment and the motion of the individual (J. J. Gibson 1979/2015; Mantel, Stoffregen, Campbell, and Bardy 2015; Stoffregen, Mantel, and Bardy 2017). When the information specifies relevant individual-environment relations, individuals perceive opportunities for action, that is, affordances (J. J. Gibson 1979/2015). Said otherwise, through exploratory perceptual-motor activity, individuals reveal energy arrays leading to the pickup of information about affordances that is used to adapt to the environment (E. J. Gibson, 1988).

Authors have tended to differentiate between exploratory and performatory actions (J.J. Gibson, 1966; E. J. Gibson, 1988; Reed, 1996). An underlying proposal has been that exploratory action reveals information that is subsequently utilized in the control of performatory action (e.g., Kretch and Adolph, 2016). Exploration is often considered as a period of information-gathering to satisfy an intention (Adolph, Eppler, Marin, Weise, & Wechsler Clearfield, 2000; E. J. Gibson, 1988; Kretch & Adolph, 2017). In this context, exploratory and performatory actions are often differentiated as the former is thought to precede the latter in development. Whilst such distinction has been meaningful in the developmental psychology literature when applied to other domains of psychology such as expert perceptual-motor control in sport, this has led to the development of methods that separate the reciprocity of perception-action (e.g., McGuckian, Cole, Chalkley, Jordet, and Pepping 2018). Indeed, a contemporary view of perception-action, that builds on James

1 Gibson's (1966) original perspective is that the process of visual perception is context-  
2 dependent and relative to the body and action capabilities of the performer (Wagman &  
3 Morgan, 2010). Although this view is well-established in ecological psychology, this  
4 important proposal is often omitted in the sports skill acquisition literature, particularly during  
5 intervention studies aimed at examining the role of exploratory movements in learning.

6         Given that a central tenet of ecological psychology is that perception is embedded in  
7 the continuous flow of action and vice-versa, in the current manuscript, we aim to develop a  
8 view of exploratory and performatory action that reflects an embodied-embedded approach to  
9 skilled behavior (Richardson, Shockley, Fajen, Riley, & Turvey, 2008). We argue that  
10 studying the dynamics of changes in exploration during learning could provide valuable  
11 information on how perception-action is developed, with specific consideration of how  
12 learners become more skilled at perceiving and acting in relation to affordances with respect  
13 to sport-specific behaviors (Ludovic Seifert, Komar, Araújo, & Davids, 2016). Central to this  
14 view is an affordance-based control framework (Fajen, 2005), which proposes two learning  
15 processes in the development of perception and action: (i) attunement and (ii) calibration.  
16 First, attunement is characterized by the differentiation of information that supports the  
17 pickup of more reliable patterns in the energy arrays to guide action (Fajen & Devaney, 2006;  
18 J. J. Gibson, 1966). Second, calibration consists in finding an appropriate scaling between  
19 information and action capabilities (Fajen, 2007). Indeed, as individuals' action capabilities  
20 change over time (e.g., action capabilities can change with fatigue), recalibration facilitates  
21 continuous adaptation that supports the visual control of action (Fajen, 2005, 2007). Despite  
22 the large body of literature discussing the importance of exploration to develop perception-  
23 action, exploratory activity is rarely studied in sports skill acquisition. To address this gap in  
24 the literature, we propose the need to examine the exploratory actions used to generate and

1 scale reliable information for affordances, to better understand “how” individuals become  
2 more skilled during learning.

3 In sum, this critical review will focus on how exploratory activity can give rise to  
4 perception-action during the acquisition of perceptual-motor skills in sport. We will first  
5 consider the methods used in ecological psychology to investigate exploration. Although this  
6 distinction appears insightful to understand the development of action systems (Reed, 1996),  
7 we propose that these methods cannot be applied to all performance contexts. Indeed, in many  
8 complex sporting environments such as climbing (L. Seifert et al., 2018), exploratory and  
9 performatory actions can appear tightly linked in tasks where performers need to continuously  
10 adjust their relationship with the environment to guide on-going and future activity. Second,  
11 we consider the dynamics of exploratory activity during learning. In studies of expert sport  
12 populations, it is often implied that the amount of exploration decreases as performers become  
13 more attuned to the relevant properties of the environment (Mann, Williams, Ward, & Janelle,  
14 2007). We will discuss such assumption and present exploration as a process that, under  
15 appropriate practice conditions, supports attunement and calibration, thus, continuously  
16 revealing the appropriate fit between the environment and the perceiver’s action capabilities.  
17 Finally, we will present some challenges and considerations to design interventions where  
18 individuals can learn to explore. Rather than learning a specific movement, we propose that  
19 skill acquisition should focus on how performers could develop exploratory behavior: (i) that  
20 is useful in various performance contexts; and (ii) that enables maintenance of active  
21 prospective control during performatory activity.

## 22 **Explore to Reach a Task-Goal: Exploration and Performance**

### 23 **Exploratory Actions: Explore to Perform**

24 James Gibson (1966) proposed that perception is an active process that does not rely  
25 on passive sensory units, but on the activity of perceptual systems. Gibson differentiated

1 exploratory (or investigative) activity achieved by these perceptual systems from the  
2 performatory (or executive) activity achieved by the action systems. Following Gibson's  
3 initial work, Reed (1996) further differentiated exploratory and performatory activities to  
4 understand the development of functional systems, which are the systems that enable  
5 individuals to use resources in their environment to achieve their goal. Reed (1996) proposed  
6 that exploratory actions are those that are aimed at scanning the environment for information  
7 whereas performatory actions are those that alter the substances and surfaces of the  
8 environment. This distinction is useful as animals, especially those like humans, with a head  
9 differentiated from the rest of the body, are able to scan their environment for information  
10 while acting in their environment. For example, during bipedal locomotion, humans have the  
11 capacity to maintain a prospective control in locomotion or to initiate other activity (Reed,  
12 1996).

13         The differentiation between performatory and exploratory activity is in line with  
14 perspectives in developmental psychology (E. J. Gibson, 1988). Eleanor Gibson differentiated  
15 performatory actions from exploratory actions that are information-gathering, to understand  
16 how infants discover opportunities for action. For instance, E. J. Gibson et al. (1987)  
17 measured the visual and haptic exploration of infants in a task where they had to traverse  
18 different surfaces. Exploratory activity was defined as the period before initiation of  
19 locomotion on the manipulated surface (i.e., when the infants were leaving a starting  
20 platform). This study showed that the duration of haptic and visual exploration depended on  
21 the properties of the surfaces (whether they were rigid or not) and on the mode of locomotion  
22 that was characteristic of the infants' developmental stage. Thus, this distinction of  
23 performatory and exploratory activities appears valuable to understand how infants developed  
24 their action systems and perceive new affordances. For example, in a series of experiments,  
25 the exploratory activity of children of different ages and abilities were studied in a task

1 requiring them to approach a slope to study whether they perceived the slope as “crossable” or  
2 not (Adolph, 1995; Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997; Adolph, Eppler, &  
3 Gibson, 1993; Adolph et al., 2000; Adolph & Eppler, 1998). In these studies, all actions  
4 (whether visual or haptic) that occurred before each child passed the edge of the slope were  
5 considered as exploratory actions. The possibilities of performatory actions are minimal in  
6 young infants as their action systems are not well developed (E. J. Gibson, 1988). Therefore,  
7 the distinction between exploratory and performatory action enables description of the links  
8 between infants’ activity and the attunement of their perceptual-motor system (Adolph et al.,  
9 1993; Eppler, Adolph, & Weiner, 1996; E. J. Gibson et al., 1987).

10         The distinction between exploratory and performatory actions in developmental  
11 psychology has motivated studies in the sport of climbing that have investigated the effects of  
12 anxiety on affordance perception (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008; Pijpers,  
13 Oudejans, & Bakker, 2005; Pijpers, Oudejans, Bakker, & Beek, 2006). In these works, the  
14 visual fixations and hand movements of climbers have been categorized as being either  
15 exploratory or performatory based on the actions utilized to complete the climb. If the action  
16 led to a displacement of the climber on the route, it was deemed performatory, otherwise the  
17 action was deemed exploratory. Results showed that both exploratory and performatory visual  
18 (eye) and haptic (hand) movements increased in high anxiety conditions, suggesting that the  
19 climbers performed at a level equivalent to novice performance (Pijpers, 2006). Further to  
20 climbing studies, researchers have also differentiated between exploratory and performatory  
21 actions in soccer. Specifically, in these works, studies have measured visual exploratory  
22 activity (VEA), separate from performatory actions (Jordet, 2005; Pocock, Dicks, Thelwell,  
23 Chapman, & Barker, 2019), with VEA defined as head and body movements that are used to  
24 scan the environment (pitch, teammates, and opponents) prior to receiving the ball, whereas  
25 performatory actions are those observed once a player is in possession of the ball. The



1 differentiation between VEA and performatory action has led to the development of  
2 experimental methods that have studied VEA in response to video images presented across  
3 multiple screens, without any game-specific performatory action (McGuckian et al., 2019;  
4 van Andel, McGuckian, Chalkley, Cole, & Pepping, 2019). Thus, a methodological  
5 consequence of creating a dichotomy between exploratory and performatory actions is that  
6 researchers have studied perception and action as two separate processes, which compromises  
7 the theoretical view of Gibson (1966). Similarly, in climbing, the differentiation of  
8 exploratory and performatory hand movements has been questioned as in many instances, it is  
9 possible that movements categorized as being exploratory may actually be “failed”  
10 performatory movements (Orth, Button, Davids, & Seifert, 2016). For instance, a climber may  
11 have tried to use a handhold, but because the handhold depth was not as expected, he/she may  
12 have only touched the handhold, released it, and then used another hold. Thus, even “failed”  
13 performatory actions may have temporary performance consequences, they remain important  
14 in the process of learning to differentiate information (van Dijk & Bongers, 2014). Thus,  
15 during practice, the entire activity (i.e., both exploratory and performatory actions) contributes  
16 to their perceptual learning.

17 In summary, actions have tended to be categorized according to their outcomes: if they  
18 enable the performer to reach the task-goal they are performatory actions, otherwise, if they  
19 lead to the discovery of available information and preparing the performatory actions, they are  
20 related to exploratory activity. Thus, exploratory activity relates to actions that aim at  
21 gathering or scanning information before the initiation of a performatory action. Considering  
22 the reciprocity of perception and action, the study of prospective control with the distinction  
23 between “action to perceive” (exploratory activity) and “action to realize the intention”  
24 (performatory action) appears to be in contradiction to the unity of perception-action.

25 **Exploration is Continuous and Multimodal: Exploring is Performing**

## 1           **Exploration Never Ceases**

2           As considered in the previous section, the differentiation between exploratory and  
3           performatory actions has contributed important understanding in developmental studies  
4           (Adolph, 1995; Adolph et al., 1997, 2000; Adolph & Eppler, 1998), where infants face the  
5           task of perceiving whether to act or not (e.g., walking down slopes or walking over an  
6           unexpected surface). However, in numerous sports activities, performers are in continual need  
7           of adapting their ongoing activity and are, therefore, unable to necessarily stop and “explore”  
8           their environment. For example, performance in pole vaulting necessitates that athletes adjust  
9           the pole position whilst running at high-speed to accurately point the tip of the pole to the  
10          vault box, and then prospectively control when and how to move relative to the pole to  
11          convert maximal kinetic energy into gravitational potential energy while avoiding the bar.  
12          Indeed, performance environments are often dynamic and require to continuously perceive the  
13          opportunities for action relative to ongoing events (Fajen, 2005; Fajen, Riley, & Turvey,  
14          2008).

15          The ability to anticipate future states of the individual-environment relation is a  
16          characteristic of all animals, especially skilled performers in sport (Araújo, Hristovski, Seifert,  
17          Carvalho, & Davids, 2017). For instance, in a series of recent climbing studies, Seifert and  
18          colleagues have found that performers do not appear to perceive the actions enabled by each  
19          separate hold during an ascent, but rather, they perceive a chain of movements offered by the  
20          properties of the holds and layout on the wall (L. Seifert et al., 2018; Ludovic Seifert, Cordier,  
21          Orth, Courtine, & Croft, 2017). Moreover, in dynamic environments such as soccer games,  
22          players may act by anticipating a chain of actions to score or defend, but they continuously  
23          need to probe for potential changes in the ball, teammates, and opponents’ movements that  
24          could affect the viability of their chain of actions (Dicks, Araújo, & van Der Kamp, 2019).  
25          The concept of nested affordances, which emphasizes that seemingly discrete behaviors are

1 better understood as a continuous flow of actions distributed across different temporal and  
2 spatial scales, may, therefore, help to understand how individuals efficiently chain their  
3 actions to achieve a task-goal.

4         The concept of nested affordances was further developed by Wagman (2012), who  
5 demonstrated the effect of practice on the estimation of reachability, revealing that affordance  
6 perception depends on the future states by which a behavior will occur. Specifically,  
7 Wagman, Cialdella and Stoffregen (2018) proposed that affordances can be nested in a  
8 hierarchy that consists of three levels: the “Why” level, which represents the task goal; the  
9 “What” level, which represents the specific behaviors needed to achieve the task goal; and the  
10 “How” level, which represents the various means available to achieve the task goal (Wagman  
11 et al., 2018; Wagman & Morgan, 2010). For illustration, Wagman (2012) showed that  
12 individuals could estimate their maximum touching height (the “Why” level) when they were  
13 asked to reach a suspended object (the “What?” level) by (i) standing on toes or standing with  
14 heels touching the ground, (a first “How?” level), and/or by (ii) using (or not using) a tool (a  
15 second “How?” level). These results indicate that individuals are able to perceive the future  
16 state of their action capabilities even when they are about to perform a series of nested  
17 actions. Therefore, there is not an exploratory action that dictates what and how to do the next  
18 performatory action, but exploration enables performers to keep on accurately perceiving and  
19 acting.

20         In accordance with the nested affordances perspective, we propose that exploration  
21 could also be considered as an aspect of performatory activity. For instance, in a team sport  
22 such as soccer, the player in possession is not the only sportsperson on the field “performing”.  
23 All the other players are also acting in such a way that they seek to probe future actions, and  
24 at the same time, they move to create opportunities for passes or to restrict opportunities  
25 (depending on whether their team is in possession of the ball or not). Thus, performers in

1 team sports are constantly scanning, probing and acting in their environment in such a way  
2 that the differentiation between exploration and performatory periods is ambiguous.  
3 Moreover, when a performer tries to dribble past his/her opponent, he/she may use deception  
4 to influence his/her opponent and guide future actions. That is, as the player is revealing and  
5 picking up information, he/she is also generating information. Thus, expertise may reside in  
6 the continuous exploratory activity of performers that enables them to maintain an active  
7 prospection of the available information to act effectively (Pocock et al., 2019). In sum, the  
8 prospective control of action occurs through the information-movement coupling, which  
9 enables to continuously adjust the relation between individual and environment to achieve the  
10 task-goal (Araújo et al., 2017). On-going actions reveal information that contribute to  
11 perception of affordances related to this action (Franchak, van der Zalm, & Adolph, 2010).

### 12 **Exploration is multimodal**

13 The continuity of exploratory activity is also dependent on multimodal perception. An  
14 important emphasis of James Gibson (1966) was that the environment is not perceived  
15 passively in which our actions are responses to stimuli, but that we actively perceive the  
16 world through the actions of the different perceptual systems. However, a multimodal account  
17 of exploration is lacking in the study of sport skill acquisition. Notably, visual exploration has  
18 largely been studied using video-based laboratory tasks where the opportunities for action are  
19 severely compromised and not representative of complex sport environments (Mann et al.,  
20 2007; McGuckian, Cole, & Pepping, 2018). Indeed, results have revealed that the gaze  
21 behaviors utilized by soccer goalkeepers when attempting to save penalty kicks change as a  
22 consequence of both the environment (i.e., video presentation vs. real-time opponent) and the  
23 response requirements (e.g., simulated movement vs. diving to save the kick) (Dicks, Button,  
24 & Davids, 2010).

1           Comparable to the study of sport performers, the role of exploration in the perception  
2 of affordances has also been studied in laboratory tasks, with restrictions placed on participant  
3 behavior. For instance, Pepping and Li (2008) investigated the role of visual and haptic  
4 exploration on the perception of maximum jumping height from different surfaces. One group  
5 of participants was allowed to explore visually and haptically (i.e., they were invited to jump  
6 on the different surfaces) whereas another group was limited to visual exploration. Although  
7 the haptic exploration group could access more information, they did not improve perception  
8 of their jumping capabilities. Rather, they overestimated their capabilities, whereas the  
9 participants in the visual exploration group underestimated them. Thus, the results indicate  
10 that limiting the perceptual systems during exploration, does not appear to support accurate  
11 attunement or calibration. Indeed, methods that have constrained the modes of exploration,  
12 have also been used to study the perception of “sit-ability” under different leg lengths (Mark,  
13 Balliett, Craver, Douglas, & Fox, 1990), gap “cross-ability” (Mark, Jiang, King, & Paasche,  
14 1999), the “catchableness” of fly balls (Oudejans, Michaels, Bakker, & Dolné, 1996) and the  
15 minimum passing height of a barrier when using a wheelchair (Yu, Bardy, & Stoffregen,  
16 2011; Yu & Stoffregen, 2012). In these studies, the limitations on the permitted actions with  
17 the different perceptual systems (e.g., notably the haptic system and visual system) has been  
18 shown to negatively affect the perceptual judgements of participants in comparison to  
19 conditions where they are able to freely explore. Such findings support a multimodal account  
20 of exploration and as such, examination of the temporal organization of different exploratory  
21 actions provides the opportunity to better understand how multimodal exploration can give  
22 rise to skilled perception-action.

23           Research conducted in the developmental psychology literature has highlighted the  
24 necessity of multimodal exploration by showing that the information picked-up through the  
25 different perceptual systems is used to support accurate affordance perception. For example,

1 in the “walk on slope” experiment, Adolph and Eppler (1998) revealed that infants can obtain  
2 visual information about depth and slant, whilst haptic exploration is required to get  
3 information about friction. Furthermore, Adolph, Eppler, Marin, Weise, and Wechsler  
4 Clearfield (2000) described the exploratory activity of infants during the “walk on slope” task  
5 as a sequential process composed of three modes of exploration: exploration from a distance  
6 (e.g., looking at the slope); exploration via direct contact (e.g., touching the slope surface);  
7 and exploration of alternative means (e.g., crawling instead of walking). Following this idea  
8 of a sequential organization of exploration, Kretch and Adolph (2017) proposed that the mode  
9 and organization of exploration in space and time is relative to its cost in terms of effort, time,  
10 and injury risk. According to this hypothesis, individuals use the exploration modes following  
11 a ramping-up organization process. For instance, haptic exploration is a risky form of  
12 exploration because it involves direct contact with an unknown surface, thus, it is only used to  
13 obtain new information following less exposed forms of exploration such as visual  
14 exploration that can be achieved from a distance and, therefore, with limited risks. Thus,  
15 exploratory activity appears to be organized in space and time when individuals search for  
16 opportunities for actions. A closer look at how haptic, motor, and visual exploration are linked  
17 during tasks is required to reveal the organization and changes in organization of exploration  
18 to maintain prospective control during action.

19       Stoffregen, Mantel, and Bardy (2017) reinforced the importance of multimodal  
20 exploration by proposing that perception should be considered as emerging from a single  
21 perceptual system rather than from different perceptual systems. This idea follows the global  
22 array hypothesis, which proposes that the senses function as a single unit during (active)  
23 perception (Stoffregen & Bardy, 2001). Studies have shown that exploratory activity can  
24 reveal higher order information to perceive the absolute distance from a target object, which is  
25 composed of optic flow patterns and haptic/gravito-inertial stimulation (Mantel, Bardy, &

1 Stoffregen, 2010; Mantel et al., 2015). These results argue in favor of looking for organization  
2 in the different dimensions of exploratory activity rather than in isolated perceptual systems.  
3 For instance, affordance perception depends on information exploited by the eyes, head and  
4 whole-body in motion, as studies have shown that eye-height information is important for  
5 calibration of the perceptual system to perceive whether one can sit on a seat or fit through a  
6 doorway (Franchak et al., 2010; Mark, 1987; Mark et al., 1990). The information-movement  
7 couplings utilized during exploration may, therefore, provide individuals with the ability to  
8 act purposefully to reveal information. Subsequently, the usefulness of the revealed  
9 information depends on the organization of individuals' exploratory actions. Thus,  
10 exploratory activity is not only an information-gathering activity that occurs before the start of  
11 performatory actions, but it is embedded throughout the entirety of a performer's activity.  
12 Exploration is multimodal as individuals do not perceive the environment through isolated  
13 perceptual systems, but as a whole. From this whole, individuals must find functional patterns  
14 to discover affordances, which is made possible through attunement and calibration of the  
15 perceptual-motor system. But how can performers become sensitive to properties of their  
16 performance environment? How does exploration evolve with practice and experience in a  
17 task?

### 18 **Exploration During Practice: Learning to Reveal Information**

#### 19 **Dynamics of Exploration: Toward Less Exploration with Practice?**

20 When exploration is investigated as a sequence of information-gathering actions,  
21 research has shown that exploratory activity tends to decrease with practice, and performatory  
22 activity also decreases as individuals attune to more reliable information and become more  
23 skilled in the task (e.g., Seifert, Boulanger, Orth, and Davids 2015). Quantification of  
24 exploratory actions has been studied during climbing, within which participants were  
25 instructed to climb three different routes - with different orientations of handholds – as

1 fluently as possible (Orth, Davids, & Seifert, 2018; L. Seifert et al., 2015). In these studies,  
2 the handhold orientation in the climbing route and experience of participants in the task  
3 impacted the amount of exploration of climbers. Specifically, the number of exploratory  
4 actions decreased with practice and increased with the complexity of behavior specified by  
5 the climbing routes. Similar findings have been observed in the development of tool creation  
6 (van Dijk & Bongers, 2014). In this study, van Dijk and Bongers differentiated between  
7 distinct periods during task completion: (i) a visual phase; (ii) a manual and visual exploration  
8 phase; and (iii) a construction phase. The first two phases were considered as exploratory  
9 activity while the construction phase was related to performatory activity. The distinction  
10 between the exploratory and performatory periods was defined relative to the initiation of a  
11 movement that was aimed at achieving the task (i.e., to create and use a tool with the pieces  
12 provided). The duration of the two exploratory periods decreased with practice, whilst actions  
13 during these phases were found to be more goal-directed, as the actions were oriented towards  
14 constructing the final tool. The authors concluded that actions became more goal-directed  
15 with the attunement of the participants to their environment and the discovery of new  
16 possibilities for action. In sum, these findings suggest that the amount of exploration  
17 decreases as the performers become better attuned to relevant information about affordances.

18         However, focusing analysis solely on the amount of exploration may be misleading.  
19 For example, Wagman, Shockley, Riley and Turvey (2001) examined how the accuracy of  
20 participants' estimations of the width and height of different objects differed following  
21 periods of haptic exploration completed under different modes of practice (i.e., with or  
22 without knowledge of results). Results revealed that irrespective of the feedback received,  
23 exploration time and exploration complexity (e.g., randomness in hand movements)  
24 decreased, which suggests that exploration decreased and gained in goal-directedness (cf. van  
25 Dijk and Bongers 2014). Nevertheless, attunement did not occur for the groups without



1 knowledge of results; in this case, the decrease in exploration time was not associated with  
2 improved performance in the size estimation of objects. This finding is in line with infant  
3 locomotion studies, which have reported that neither the amount nor the type of exploration  
4 predicts motor decisions (Adolph et al., 2000; Joh & Adolph, 2006; Kretch & Adolph, 2017).  
5 Therefore, an increase in the effectiveness of exploration cannot be explained solely through  
6 the measurement of the quantity of exploration; a measure that accounts for the accuracy of  
7 perception is required.

8         The literature considered in this section suggests that individuals who become  
9 successful in a task do not necessarily decrease the quantity of exploration over time. Rather,  
10 it appears that successful exploration reveals the opportunities for action that fit both an  
11 individual's action capabilities and properties of the environment. Thus, successful  
12 exploration guides the pick-up of reliable information for task accomplishment; that is,  
13 successful exploration is a consequence of increasing accuracy rather than decreasing  
14 quantity. Thus, we argue in the following sections that when studying the perceptual learning  
15 processes of attunement and of calibration, it is more insightful to investigate changes in  
16 performers' exploration during practice rather than the volume of exploration.

### 17         **Explore to Reveal Reliable Information: Differentiation of Information**

18         Perceptual learning studies have demonstrated that, with practice, novices can learn to  
19 exploit more reliable informational variables through the attunement of the perceptual systems  
20 (Jacobs & Michaels, 2006; Smith, Flach, Dittman, & Stanard, 2001; van der Kamp,  
21 Savelsbergh, & Smeets, 1997). To better understand the relation between exploration during  
22 learning and task achievement, an important question is whether the changes in the pick-up of  
23 information are a consequence of changes in the mode of exploration. For instance, van Dijk  
24 and Bongers (2014) observed the functional reorganization of gaze behavior with practice in  
25 their tool making task. This reorganization had both an exploratory role, which led to the

1 pick-up of information about affordances, and a performatory role, which led to alterations of  
2 the environment that led to the discovery of new affordances. Given the mutuality of  
3 perception-action, changes in the information exploited may be assessed by the changes in the  
4 way individual interacts with the environment. For example, Withagen, Kappers, Vervloed,  
5 Knoors and Verhoeven (2013) investigated if sighted, and blind children and adults were  
6 using the same exploratory actions to differentiate between dimensions of an object including  
7 the shape, weight, volume and texture. The experimenters defined five exploratory procedures  
8 that they used to code the participants' hand movements. They measured the percentage of  
9 time spent using each exploratory pattern and the quality of exploration (i.e., the time needed  
10 before an estimation). Results showed that specific exploratory patterns were necessary to  
11 estimate some dimensions of the objects and that the difference between sighted and blind  
12 participants was not a result of the specific exploratory pattern utilized but in the quality of  
13 exploration (i.e., blind participants needed less time to respond). With practice, participants  
14 learnt to differentiate three out of four object dimensions (i.e., their shape, texture and volume  
15 but not their weight), which illustrated that practice led to the detection of more reliable  
16 information. Thus, the novice participants needed to find an adequate means of exploration to  
17 interact with the objects to achieve the task and, as such, they learnt how to explore.

18         Wagman (2012) pointed out that changes in exploratory actions can be obvious (e.g.,  
19 like touching a surface to estimate its walk-ability after a fall, Joh and Adolph, 2006) or more  
20 subtle (e.g., changes in head and torso motion are sufficient to judge maximum sitting height  
21 when action capabilities are changed: Stoffregen, Yang, and Bardy, 2005). In accordance with  
22 different contemporary learning perspectives in ecological psychology (Fajen, 2005; Jacobs &  
23 Michaels, 2007), it would be important to understand whether differences exist in the modes  
24 of exploration associated with changes in perceptual attunement and the calibration of action.  
25 An example of an obvious change in exploratory activity was observed in a study by Joh and

1 Adolph (2006) during which, children had to walk on a path with a hidden foam pit. Results  
2 showed that after falling in a trial, children increased the amount of exploration on subsequent  
3 trials: they took more time before walking on the path, they changed their locomotor  
4 behavior, and they increased the use of exploratory touching near the foam pit. Task  
5 achievement was due to the differentiation of reliable visual information (i.e., the delineation  
6 of the new ground surface), which was motivated by a fall in an earlier trial that guided  
7 changes in the exploratory and locomotor activity. Exploration may lead to misperception and  
8 failure in the task if the exploited information is not reliable, irrespective of the time spent  
9 exploring the environment (Adolph, Marin, & Fraise, 2001). Therefore, the quantity of  
10 exploration during learning should be investigated alongside the mode of exploration (i.e.,  
11 how do individuals reveal information to achieve the task?) and the dynamics of exploration  
12 during practice (i.e., what were the previously observed outcomes and behaviors?).

13 A recent climbing study proposed an innovative method to study the dynamics of  
14 exploration during the acquisition of a complex motor skill. To describe the temporal  
15 organization of exploration of climbers during practice, Seifert, Orth, Mantel, Boulanger,  
16 Hérault, and Dicks (2018) defined five different climbing states: (i) looking at the route; (ii)  
17 adjusting the center of mass; (iii) determining which hold to use (i.e., modifying the position  
18 or orientation of the hand or foot); (iv) hold changing (i.e., grasping another hold while the  
19 hip stays stationary before motion); and (v) moving the hip and at least one limb. The number  
20 of times each mode was used, and their relative duration was measured for each trial during  
21 practice. The authors presented the dynamics of exploration across multiple temporal levels,  
22 which enabled improved understanding on the relations between exploration during learning  
23 and task achievement. Their results revealed that climbers decreased the number of stationary  
24 states while their climbing fluency increased, suggesting an improvement in “route finding”  
25 skill, encompassing the ability to perceive a chain of movements (i.e., nested affordances) on

1 the climbing route. Such association between the dynamics of exploration and the dynamics  
2 of performance highlights changes in the efficiency of an individual's exploration. The  
3 analysis of the dynamics of the efficiency of the exploratory activity would also reveal if the  
4 learning protocol enabled individuals to learn to explore effectively, that is by guiding  
5 performers toward information about affordances relevant for the task achievement.

### 6 **Explore to (Re)Calibrate the Perceptual-motor System: Scaling Action to the** 7 **Information**

8 Although the previous section stressed that the exploration of performers may change  
9 as they increase their sensitivity to their environment, it shouldn't be forgotten that the  
10 accurate perception of affordances is grounded in the individuals' sensitivity to their action  
11 capabilities (Fajen, 2007). For example, Oudejans, Michaels, Bakker, and Dolné (1996) used  
12 an interception task to study the "catchableness" of a fly ball. To be perceived, this kind of  
13 affordance requires that participants scale information to their body size (e.g., eye height and  
14 leg length) and to their running and catching capabilities. Results revealed that participants  
15 were more efficient in judging the ball "catchability" when they could move than when they  
16 stood before giving their judgement. This difference was explained by the availability of  
17 information about the boundaries of the participants action capabilities when they are moving,  
18 which supports the view that exploration is continuous.

19 Given that action capabilities are liable to change due to motor development on a  
20 longer timescale, and on a shorter timescale, due to fatigue, calibration and recalibration must  
21 be continuous to accurately perceive opportunities for action (Franchak & Somoano, 2018).  
22 More specifically, a change in action capabilities modifies the mapping between information  
23 and action which requires recalibration, that is, to adapt the scaling of action to information  
24 (van Andel, Cole, & Pepping, 2017). Moreover, Brand and de Oliveira (2017) proposed that  
25 the exploration required for recalibration depends on the availability of reliable information

1 and on the magnitude of the disturbance of the action system. The authors subsequently  
2 suggested that expert performers may better adapt to disturbances in their action capabilities  
3 as they may have developed exploratory actions that support recalibration over a relatively  
4 short timescale (Brand & de Oliveira, 2017). For example, Mantel, Stoffregen, Campbell, and  
5 Bardy (2015) demonstrated that individuals could generate sufficient information about the  
6 distance between themselves and an object with only a combination of eye, head and torso  
7 movements. Such adaptive exploratory actions could reflect the subtle changes in exploration  
8 that we previously discussed that are used to adapt perception and action to the context  
9 (Wagman, 2012).

10         During development, children adopt different locomotion patterns including crawling  
11 and walking due to postural milestones (e.g., learning to crawl, to walk...), which requires  
12 calibration of an infant's action capabilities and contributes to the process of differentiation of  
13 information (Adolph et al., 1997; Adolph & Eppler, 1998). Indeed, experiments on the slope  
14 crossing task have revealed that infants in their first weeks are unable to judge risky slopes.  
15 Rather, they needed weeks of locomotor experience to develop exploratory activity to  
16 generate information that reveals the fit between environmental properties and their  
17 capabilities (Adolph, 2008). In fact, the emergence of new coordination modes can increase  
18 individual action capabilities and extend the field of possibilities that the environment offers  
19 to individuals. During learning, changes in patterns of coordination used to achieve task  
20 outcomes have been observed during practice (Chow, Davids, Button, & Rein, 2008; Komar,  
21 Potdevin, Chollet, & Seifert, 2019; Nourrit, Delignières, Caillou, Deschamps, & Lauriot,  
22 2003). These behavioral dynamics may induce the need for learners to modify their  
23 exploratory activity to control their movements accurately, but it also gives to the learners the  
24 chance to discover new opportunities for interaction with the environment.

1           It has been suggested that the discovery of original and functional possibilities for  
2 action (i.e., individuals' creativity) may be enhanced when individuals act close to their  
3 maximal action capabilities (Orth, van der Kamp, Memmert, & Savelsbergh, 2017).  
4 Conversely, it has been proposed that in everyday tasks, individuals tend to stay in a safe  
5 region in-between the boundaries of their action capabilities to preserve the possibility to  
6 adapt their behavior (Fajen, 2005). For instance, studies show that children playing in a  
7 climbing playscape stay within a safe region of their action boundaries and keep a security  
8 margin when they climb (Croft, Pepping, Button, & Chow, 2018; Prieske, Withagen, Smith,  
9 & Zaal, 2015). This protective behavior has also been observed in a virtual car braking task  
10 where participants anticipated braking even if they could stop later (Fajen, 2005; Fajen &  
11 Devaney, 2006). However, in competitive sport contexts, performers are pushed toward their  
12 action boundaries. In such instances, exploratory movements (i.e., like touching a hold in a  
13 climbing task to estimate its grasp-ability) may be limited so that performers are targeted in  
14 their exploration to maintain a prospective control and to perceive the limits of their action  
15 capabilities. For example, when attempting to save penalty kicks, soccer goalkeepers tend to  
16 initiate movements to intercept the ball outside of their action boundaries (Dicks, Davids, &  
17 Button, 2010). Although this late dive may not enable goalkeeper to reach for the ball if the  
18 shot is highly accurate, this timing of action allowed goalkeepers to rely on more useful  
19 spatial information to anticipate kick direction. Thus, methods that investigate affordance-  
20 based control of action should assess the maximal action capabilities of the performers to  
21 examine whether they are sensitive to their action boundaries. Also, it seems that performers  
22 should explore a large range of their action capabilities during practice to develop efficient  
23 exploratory activity, and acting close to their action boundaries may encourage performers to  
24 find new movement solutions that would extend their maximal action capabilities and their  
25 possibility of exploration.

## Learning to Explore

1  
2 A key emphasis of this critical review is that skill learning conditions in sports should  
3 encourage the development of modes of exploration that reveal the fit between environmental  
4 properties and performers' action capabilities to perceive affordances relevant for task  
5 achievement. Practice conditions should: (i) lead performers to develop exploratory activity  
6 that reveals more reliable information; and (ii) encompass safe environments where  
7 performers can learn to explore even when they behave close to – and beyond - their current  
8 maximal action boundaries. When applied to climbing, a safe environment refers to situations  
9 from which the learner can escape, fallback or adapt and use a back-up plan. To test this  
10 hypothesis, Seifert, Boulanger, Orth, and Davids (2015) designed three climbing routes by  
11 manipulating the hold orientation and the number of available edges for grasping during  
12 learning. A horizontal-edge route was designed to allow horizontal holds in which the trunk  
13 faced the wall. A vertical-edge route was designed to allow vertical holds, which experienced  
14 climbers were able to grasp with the side of their body toward the wall. Finally, a double-edge  
15 route was designed to invite both horizontal and vertical holds. Because a route with only  
16 vertical-edge holds was challenging for novice climbers, the double-edge route allowed safe  
17 and functional exploration because climbers could both exploit their preexisting behavioral  
18 repertoire (i.e., horizontal-hold grasping pattern with their trunk toward the wall) and explore  
19 new behaviors (i.e., vertical-hold grasping with their side toward the wall). The results  
20 indicate that this safe environment of practice can be useful because perceptual-motor  
21 exploration appears less risky, with possible back-up and the learner is more inclined to  
22 experiment in these regions (L. Seifert et al., 2015). Thus, this learning design guided the  
23 exploration of learners to search for reliable information to perform the vertical-hold grasping.

24 However, research has also demonstrated that if there is insufficient variation in the  
25 practice environment, learners can sometimes exploit information that does not support

1 accurate perception when they are exposed to a broader range of situations (Fajen & Devaney,  
2 2006; Smith et al., 2001). To address this issue, Smeeton, Huys and Jacobs (2013), proposed a  
3 novel type of intervention to guide learners' exploration to pick-up more reliable information  
4 by neutralizing less useful information. More specifically, they reduced the usefulness of the  
5 informational variables that were potentially used by novice tennis players to anticipate the  
6 direction of their opponent's stroke by keeping constant this potential information while the  
7 strike outcomes were varied. Two important findings revealed that: (i) learners exploited new  
8 information if the usefulness of the initial information is reduced; and (ii) learners could  
9 attune to higher order information that supported accurate perceptual-motor skill in both a  
10 post-test and transfer test (in this study, the higher-order information was distributed across  
11 different body parts of the opponent).

12 Variable practice has been proposed to guide learners' perceptual attunement and to  
13 enhance transfer of learning (Fajen, 2005; Fajen & Devaney, 2006; Huet et al., 2011). In this  
14 form of practice, less useful informational variables are varied across practice trials so that  
15 learners are forced to search for new and more consistent information to guide their action.  
16 Smith, Flach, Dittman, and Stanard (2001) proposed the concept of flexible attunement to  
17 describe the ability of learners to rely on different informational variables according to the  
18 performance context. Fajen and Devaney (2006) observed such flexible attunement while  
19 comparing the effects of different variable practice conditions to perform a braking task in a  
20 virtual environment. They manipulated either (or both) the stop sign radius and/or the initial  
21 speed of the virtual vehicle so that the less reliable informational variables, like the expansion  
22 rate of the sign would no longer be useful. Results showed that these interventions led to  
23 perceptual attunement: participants learnt to rely on high order informational variables to  
24 guide their actions. Similarly, Huet, Jacobs, Camachon, Missenard, Gray, and Montagne  
25 (2011) created a flight simulator where the less reliable informational variables initially used



1 by novice participants were varied so that exploiting this information no longer supported  
2 accurate action. Results showed that participants in the variable practice group outperformed a  
3 constant practice group in a transfer test due to changes in the informational variables used to  
4 guide action. Developing interventions that support flexible attunement (i.e., transfer in the  
5 use of a variable to guide action) is important in sports given the variable and complex nature  
6 of sport environments (Fajen et al., 2008). Dicks, Pocock, Thelwell, and van der Kamp (2017)  
7 proposed a form of on-field variable practice to train goalkeepers in a penalty task. The  
8 goalkeepers faced three players that started their run-up together but only one of them executed  
9 the penalty on each trial. This intervention was aimed at directing the goalkeeper's attention  
10 to information that emerged around the time of when the penalty taker's foot contacted the  
11 ball. Compared to constant practice (i.e., facing penalty kicks from one player executing the  
12 run-up and penalty), the intervention enhanced performances of goalkeeper on non-deceptive  
13 penalty kicks, which may be due to a better perceptual attunement. Such intervention must be  
14 developed to help learners to pick-up more reliable information about affordances, and so that  
15 the exploration developed during practice can be transferred and used to achieve high  
16 performances outside the training context.

17         Linking perspectives from ecological psychology to existing findings on the dynamics  
18 of learning may help to better understand the transfer of perceptual-motor skills to multiple  
19 contexts of performance and to inform interventions that both develop a performer's motor  
20 repertoire and guide learners toward more reliable information. Indeed, a large volume of the  
21 literature focusing on interventions in performance contexts is rooted in the dynamical  
22 systems approach to learning (Schöner, Zanone, & Kelso, 1992). This framework has focused  
23 on the effect of the interventions on coordination dynamics (i.e., the motor repertoire of the  
24 learners) rather than on perceptual attunement (Chow et al., 2008, 2007; Lee, Chow, Komar,  
25 Tan, & Button, 2014). Based on Bernstein's (1967) observation that practice is a form of

1 “repetition without repetition”, interventions have focused on the role of movement variability  
2 to develop the adaptability of learners. For instance, training interventions such as  
3 “differential learning” have proposed to add random noise to task constraints (i.e., irrelevant  
4 movement components) to increase the performance of learners by discovering multiple  
5 movement solutions (Schöllhorn et al., 2006; Schöllhorn, Hegen, & Davids, 2012;  
6 Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009). A question remains about the  
7 qualitative nature and actual relevance of the induced variability (i.e., the random noise in the  
8 task constraints). Indeed, variations in the learning contexts may encourage attunement only if  
9 reliable information is available in the different learning conditions (Smeeton et al., 2013).  
10 Cardis, Casadio, and Ranganathan (2018) have also pointed out that such variability may  
11 increase exploration of new solutions but may adversely affect the ability to retain the learned  
12 solution, thus, they questioned the threshold of variability after which variable practice  
13 impairs learning.

14 In summary, learning interventions may promote the discovery of exploratory actions  
15 that enhance the transfer of perceptual-motor skills. Learners should be given the opportunity  
16 to safely explore and to be guided toward more reliable information for action. Reducing the  
17 usefulness of the less reliable information seem to be effective in enhancing transfer of  
18 learning. In this aim, the less reliable information can be neutralized or varied across practice  
19 trials so that learners search for new and more reliable information for action. However, care  
20 must be given to the context of practice that may limit the opportunity to interact with the  
21 environment. Thus, as learning is not about accumulating information across trials but rather  
22 generating and exploiting useful information for action, interventions must lead performers to  
23 learn to explore rather than learning a model of skill.

24 **Conclusion**

1           This critical review focused on how exploratory activity can support the development  
2 of perception-action during learning. We considered that exploration is continuous and  
3 multimodal, and so, the generation and pickup of information lies in all the actions of  
4 performers. Therefore, we propose that future investigations in skill acquisition should look at  
5 the changes in the organization of the learners' exploratory activity in relation to performance  
6 achievements rather than observing the amount of exploration during practice. Experts in  
7 high-performance contexts such as sport manage to perceive future states of their relationship  
8 with their environment even though they experience changes in their action capabilities or  
9 events. Therefore, a dynamic view of exploratory activity may reveal how experts in sport act  
10 in uncertain and dynamic environments. Practice conditions must lead individuals to adopt  
11 exploratory activity that reveals the fit between the environmental properties and their action  
12 capabilities. Moreover, to discover new opportunities for action, learning environments  
13 should promote safe conditions that give performers the opportunity to develop exploratory  
14 activity, even when they act outside of a 'safe region' of their action capabilities. In this  
15 regard, interventions that guide learners to search for more reliable information appear to be  
16 the most suitable learning design to develop exploratory activity that would enhance the  
17 transfer of skill to various performance contexts.

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