3 Trading Perception and Action for Complex Cognition: Application of Theoretical Principles from Ecological Psychology to the Design of Interventions for Skill Learning

Paula Silva, Adam Kiefer, Michael A. Riley, and Anthony Chemero

> For many actions, we are aware of nothing between the conception and the execution. All sorts of neuromuscular processes come between … but we know absolutely nothing of them. We think the act, and it is done.
>
> —James, *The Principles of Psychology*, 1890

1 Introduction

A brief observation of an athlete in action readily reveals the seamless flow between intention formation and intention enactment highlighted in the quote above by William James. Consider, as an example, the set of tasks performed by a soccer player in the pursuit of scoring a goal: she moves toward the ball, intercepts it while avoiding the opponent, navigates through the field, passes the ball to an unguarded teammate, navigates closer to the left side of the goal through a gap between defenders, watches the ball as it flies back toward her, jumps up and forward at just the right time, and heads the ball toward the right upper corner of the goal, avoiding the goal keeper who is jumping leftward. If asked about the play, the athlete would likely be able to identify, in retrospect, the sequence of enacted intentions leading to goal satisfaction. The processes underlying the selection, from indefinitely many choices, of the particular movement solutions that realize these intentions are, in contrast, typically immune to conscious inspection. These processes are among the primary targets of theories of motor behavior. Hypotheses about them, whether explicit and clearly articulated or implicit and unarticulated, drive decision making of managers, trainers, coaches, and clinical sport professionals whose jobs include the challenge of facilitating the development of motor skills to optimize performance and prevent injuries. An articulated theoretical framework is preferred because the explanatory and predictive features of theory should promote the judicious selection of optimal principles for practice and interventions, including the design of training technologies.

In this chapter, we present and discuss the ecological approach to motor behavior, which provides a radically embodied and embedded perspective on the processes that support the flow between intention formation and action execution (Chemero 2009). This approach is contrasted with the more traditional information-processing approach to motor behavior, with two particular aims. The first is to provide evidence that the hypothesized, complex cognitive processes implicated by the latter approach can be greatly simplified, if not fully dismissed, when we consider the constitutive role of perception and action in intention formation and action execution. The second is to demonstrate how this principle (which is the power of an embodied, embedded perspective) can inspire innovative and transformative approaches to skill learning in sport settings and beyond. We do so by elucidating how the different views on the processes supporting motor behavior lead to very different proposals for how to use visual feedback to promote learning of optimal movement execution.[1]

2 Explaining Motor Behavior: What Is the Challenge for Theory?

Skilled motor performance is supported by movement patterns characterized by two related features of movement: effectiveness and efficiency (Guthrie 1952). Movement effectiveness is determined by the extent to which it promotes accurate and consistent achievement of the intended functional outcomes. Movement efficiency is determined by the level of physical and mental effort involved in the achievement of those outcomes. Physical effort has been indexed, for instance, by the energy expenditure or biomechanical stress associated with a movement pattern supporting task performance (Lay et al. 2002; Sparrow et al. 1999; Sparrow and Newell 1998). Mental effort relates to cognitive demands (attention, memory, etc.) involved in movement organization, and has been indexed by the level of performance on a secondary task (Smith and Chamberlin 1992). Any theoretical account of the processes supporting motor behavior must explain how individuals successfully achieve movement solutions for task performance that are both effective and efficient.

The seemingly automatic link between action conception and execution that is a hallmark of our daily experiences does not help us see the complexity of the problem biological movement systems evolved to solve. Bernstein (1967), better perhaps than anyone else before him, envisioned such complexity and, consequently, set specific challenges for theories of motor behavior (Turvey 1990). First and foremost, he drew attention to the fact that any activity, from mundane to highly skilled, involves a very large number of components (neural, muscular, skeletal, etc.) that vary in structure and function and that operate at various temporal and spatial scales. The movement pattern required to effectively and efficiently achieve a desirable functional outcome has to be produced through the organization of these many components that together constitute our action system. Importantly, the number of dimensions that defines the action system implicated in a given task (e.g., the arm for reaching) is much higher than the number of dimensions that defines the task. For example, reaching with the arm for a particular object while placing the hand at a particular orientation yields a task space that is six-dimensional, defined by three spatial dimensions of position and orientation about three spatial axes. The arm, described at the coarse scale of the joints, consists of seven spatial degrees of freedom (rotation about three axes in the shoulder, one in the elbow, two in the wrist, and pronation-supination of the forearm). The implication of this kinematic redundancy is that there are indefinitely many combinations of joint movements and related neuromuscular patterns (hereafter simply "movement solutions") that could be used to realize a particular intention. Put differently, there is a many-to-one mapping between potential movement solutions and functional outcomes. In light of the abundance of choices the movement system can make (Gelfand and Latash 1998), what constrains selection of a particular pattern?

Task performance, particularly in athletic and sport contexts, is embedded in dynamic environments. Reliably achieving intended outcomes (i.e., movement effectiveness) thus implies that contextual conditions must necessarily constrain the processes supporting flexible and adaptive selection of movement solutions. For example, a soccer player intercepting the ball with the head will do so using very different body movements every time depending, for instance, on their position with respect to the ball and to players from the opposing team. Controlled experimental studies have consistently demonstrated this phenomenon in the laboratory: movement solutions displayed by expert performers exhibit context-sensitive variability (Kelso et al. 1984; Steen and Bongers 2011; Wilson et al. 2016). Variability is structured so as to stabilize relevant performance outcomes (Latash 2012; Latash, Scholz, and Schöner 2002), and action organization seems to imply selection of a family of movement solutions, not just a particular one (Latash 2010).

Movement solutions will be efficient in addition to effective if they exploit (and not simply compensate for) forces provided "for free" by the body and task environment. Examples of these forces include the gravitational field and the elastic field of the body created by muscles and connective tissues. Effective gait patterns, for instance, exploit pendular dynamics in a way that optimally conserves potential energy from cycle to cycle (Holt, Fonseca, and LaFiandra 2000; Holt, Hamill, and Andres 1991). Similarly, the mass-spring dynamic characteristic of running patterns optimally exploits the elastic properties of muscles and connective tissues to reduce the need for metabolic energy generation (Farley, Glasheen, and McMahon 1993). The charge of processes supporting movement effectiveness and efficiency is, therefore, to "bend" the force field provided "for free" by the context to generate the overall force structure that is required for successful behavior (Bernstein 1967; Turvey, Fitch, and Tuller 1982). A key question to be answered by theories of motor behavior can, therefore, be formulated as follows: What is the nature of the processes supporting movement effectiveness and efficiency across variable and dynamic contexts?

3 The Information-Processing Approach to Motor Behavior

The information-processing approach to motor behavior maintains logical coherence with the classical view of cognition (Chomsky 1975; Fodor 1975; Pylyshyn 1980) in that it assumes that the processes supporting movement effectiveness and efficiency implement computations over representations. Consider, as an example, theories of motor behavior inspired by engineering control theory principles, such as optimality (Flash and Hogan 1985; Harris and Wolpert 1998; Kawato 1999; Wolpert and Kawato 1998). According to these theories, skilled performance of a particular task is the product of (a) the computation of a family of movement solutions to achieve a *represented* goal state (e.g., the coordinates in space where a soccer ball must be intercepted); (b) selection of the one solution that minimizes a predetermined optimality criterion (e.g., jerk, effort, noise); and (c) execution of the motor plan by the peripheral neuromuscular system. This style of control predicates a purely cognitive planning stage that precedes and is logically independent from the action execution stage (e.g., Glover 2004). As a result, the dynamics of action execution cannot directly inform or shape the planning process.

Representational structures hypothesized to be involved in motor planning have been variously referred to as motor engrams, programs or schemas (Keele 1968; Schmidt 1975), and internal inverse (Kawato, Furukawa, and Suzuki 1987; Shadmehr and Mussa-Ivaldi 1994) and forward models (Kawato 1999). The idea common to these various approaches is that the nervous system drives the movements of body segments during task performance by deploying a largely preconceptualized plan. It does so supported (in the more recent variations on the original motor program theory) by sensory input about contextual conditions. Because processing sensory input takes time, information available for selecting the course of behavior at a given moment is always about something that happened a few milliseconds earlier. To circumvent this problem, more recent theories of motor performance that fall under the information-processing approach conceptualize the brain as a predictive device. Those approaches postulate that the nervous system builds representations of the world and models of the body that are used to continuously generate predictions of what will happen next and parameterize movements accordingly (see, e.g., Jordan and Wolpert 1999). These predictions take the form of sensory states that would be expected to occur in the future (the anticipated future state of the movement system) based on a copy of the motor commands issued to muscles and internalized knowledge about the body and task environment. The course of behavior is proposed to be selected by a neural implementation of an estimator, such as a Kalman filter (Denève, Duhamel, and Pouget 2007; Todorov 2004). The key property of this filter is its ability to combine the estimated future state with (delayed) sensory feedback to provide a basis for computing motor commands that will be appropriately adjusted to upcoming conditions (Denève, Duhamel, and Pouget 2007). The effectiveness of the estimator in predicting changes in context and their consequences for movement outcomes in real time depends on two factors: the fidelity of the representations of the world and the body supporting the predictions, and the accuracy of the (often complex and nonlinear) calculations of the muscular torques required to achieve a desired spatial trajectory. Therefore, the quality of performance depends on the quality of the representations and of the computations over these representations.

In sum, according to the information-processing approach to motor behavior, movement effectiveness and efficiency is achieved by a neural implementation of an inference engine that distills a *future-looking* rule. This rule is a particular sensory-motor transformation (or sensory input–motor output relation) that sustains the desired functional outcome under variations in context. The computational processes generating these inferences can be expected to be quite complex considering (a) the high dimensionality of the action system, (b) the nonlinear and context-dependent relation between a motor command or muscle activation and the resulting movement, and (c) the presupposed ambiguous mapping of sensory input to the contextual conditions that generated them (see Ostry and Feldman 2003, for an extensive critique of internal model approaches). Importantly, the computational processes supporting control of motor behavior proposed by modern information-processing accounts are considerably more flexible in comparison with the processes proposed by the original motor program approach (Keele 1968). Modern accounts do not assume, for example, that all motor behavior is open-loop. The gain in flexibility, however, comes at the cost of greater computational and representational demands. In other words, the gain in flexibility can be attributed to increasing the complexity and sophistication of the cognitive processes proposed to explain successful movement planning (Jordan and Wolpert 1999; Kawato 1999). In the pages that follow, we present an alternative theoretical approach that emphasizes the constitutive role of perception and action in intention formation and action execution. The approach does not require invoking complex cognitive processes and related representational content, and thus stands to offer a more parsimonious account of movement effectiveness and efficiency than the cognitive approaches described thus far.

4 The Ecological Approach to Motor Behavior

The ecological approach to skilled motor performance, proposed by James Gibson (1979) and subsequently developed by others (Lee 1976; Michaels and Carello 1981; Shaw, Kugler, and Kinsella-Shaw 1990; M. T. Turvey and Carello 1986; Michael T. Turvey et al. 1981; Warren Jr. 1998; Warren 2006), stands in sharp contrast to the information-processing approach just described. In particular, the ecological approach attempts to explain the organization of action without resorting to representations or internal models. Two key concepts carry most of the load in meeting this challenge: affordances and information (Fajen et al. 2009).

Affordances are opportunities for action offered by the environment to an individual when certain relevant individual-environment relations are obtained (Michaels and Carello 1981). Therefore, affordances can be considered a source of knowledge, off-loaded onto the environment, about the means to accomplish a task. For the sake of illustration, consider again the set of actions taken by the soccer player described at the beginning of the chapter. The particular choices she made reflect the affordances that emerged and were discovered as she engaged with the dynamic task environment: an opponent struggling to control the ball after a bad pass afforded ball stealing; an unmarked teammate afforded passing the ball as she approached opponents; a gap between opponents afforded moving through to approach the goal; the ball reaching the peak of its trajectory in front of her afforded heading the ball to score a goal. Notice that we listed the affordances in shorthand, that is, without mentioning the characteristics required of the individual for their actualization. For example, a soccer ball arcing through the air affords heading to the goal only to individuals with the ability to jump to a particular height at a particular time. Therefore, an individual's capabilities relative to the environment determine what behaviors are afforded in a particular situation (Kadar and Shaw 2000; Shaw 2001). If affordances can be perceived—which a large body of research suggests is the case (see Fajen et al. 2009)—then it is possible that they support a continuous flow from intention formation to action execution, leading to goal satisfaction.

Perception of affordances requires information about them. Information, in the ecological approach, refers to ambient energy fields (optical, mechanical, acoustic) that are structured by objects and surfaces in the environment and by perceivers' dynamical relations to them created during activity (Gibson 1979). The structure in ambient energy arrays is lawfully determined. For example, the patterning of optical energy available at a point of observation (i.e., the optic array) is not ambiguous; it is specific to a particular relation of the observer to the environmental layout and, therefore, can be reliable information about affordances. The implication is that perception of affordances does not need to be construed—as is needed from a traditional information-processing perspective (Fodor 1975; Knill and Richards 1996; Marr 1982)—as the process of inferring the most likely distal stimulus based on an ambiguous proximal stimulus (e.g., in the case of vision, a distorted, upside-down, two-dimensional retinal image). Instead, perception can be *direct*, meaning that it is based on the detection of information that unambiguously specifies the animal-environment system (Gibson 1966, 1979). If the information available to perceivers is not ambiguous, as has been traditionally assumed, then there is no theoretical motivation for computational and representational processes that are supposed to assign meaning to ambiguous sensory data, and perceivers can be said to be in epistemic contact with the world rather than with a mental representation that stands in place of the world. In this view, neural processes are involved in the active detection of information, but they do not create meaning.

The research program of the ecological approach involves determining what informational variables could regulate behaviors, such as catching, hitting, and locomotion. Again, information is viewed as regulating action directly, in a task-specific manner. Many studies provide empirical support to this idea (Fajen 2005a, 2005b; Fajen et al. 2003; Michaels, Jacobs, and Bongers 2006; Peper et al. 1994; Warren et al. 2001; Zaal and Bootsma 1995). Results of these studies show that movement solutions can be mapped to optical patterns (informational variables) that emerge when an individual engages with a particular task environment. For example, control of forward and backward displacement when catching a ball can be mapped to the acceleration or trajectory of the ball in the visual field—catchers move so as to cancel optical acceleration or to linearize the optical trajectory of the ball; by doing so, they arrive at the right place, at the right time, to catch the ball (Chapman 1968; Oudejans et al. 1996). Action selection can be understood, from this view, as the selection of a set of movement solutions that creates and sustains a desired low-dimensional pattern of stimulation—the pattern of stimulation specifying the animal-environment relation that leads to goal satisfaction.

The power of the ecological approach comes from an understanding of information that both regulates and is generated by the activity of animals. For instance, when an individual navigates toward an object, she controls her locomotion by keeping the optical contour of the object at the center of optical expansion. At the same time, optical expansion is generated by the individual's motion toward the object, and the center of optical expansion changes in a one-to-one manner with changes in locomotor direction. This information, therefore, is about both the individual and her actions and about the environment in which the actions are occurring. Importantly, because the informational patterns available to the actor's perceptual systems are lawfully structured by and unambiguously specific to the animal-environment interaction, no computation or inference is required to perceive direction of heading or to use information originating in optical outflow to control the direction of locomotion. The information (about direction of heading) must be detected, but heading direction does not need to be computed on the basis of incomplete sensory data. The information is in the optic flow pattern, and is not created in the organism's nervous system (Zhao and Warren 2015).

This example illustrates how when individuals are learning a new skill they actively engage their environments and discover stable relations with it that get the task done. These actor-environment relations, in turn, select and reinforce the movement patterns that created them (Kelso and Fuchs 2016). Importantly, the lawful structuring of stimulus energy by the actor-environment relation implies that individuals can discover how to move to create particular patterns of stimulation, even without any explicit, conscious knowledge of how their movements relate to them.

To summarize, the relations between an individual and the environment supported by information about affordances allow for noncomputational explanations to action organization (see Warren 2006, for a review on noncomputational accounts). Importantly, the individual that is part of such relations can rely on stable aspects of the world (in particular its affordances) to arrive at the right movement solutions that support task performance. It is, therefore, the embedding of an individual in her environment that allows the ecological approach to sidestep the need for complex cognitive processes and related representational content implicated by the information-processing approach.

5 Affordances at Work: An Empirical Illustration

The argument that individuals perceive affordances and use them to organize context-sensitive movement solutions finds support in empirical work (Fajen 2005a, 2005b; Michaels, Jacobs, and Bongers 2006; Wilson et al. 2016). Wilson et al. (2016), for instance, demonstrated that expert throwers perceive the affordance for hitting a target by measuring how their actions changed as the affordance changed. These authors used a task-dynamic approach (Saltzman and Kelso 1987) to define the affordance space. This strategy entails a definition of the task in a way that allows the identification, through simulations, of the set of motor outputs that relate to successful performance. This set constitutes the "functional space" (or affordance) that an individual intending to perform the task must perceive.

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Wilson and colleagues (2016) characterized the task of throwing for distance and accuracy as the task of generating a projectile motion that intercepts a particular target. The task-relevant motor outputs in question were a combination of release parameters: release angle, release speed, and release height. The possible combinations of release parameters that result in hitting the target are what the target offers a to-be-thrower (or the affordance of *hitability*). Accordingly, these combinations defined the affordance space for throwing. These combinations were identified in the study in question through simulations of projectile motions. A functional, or affordance, space for throwing was created for each parameter set: a target, placed at a particular distance, orientation, and height, to be hit by a tennis ball undergoing projectile motion. Results showed that movement solutions (here a particular combination of release parameters) of expert throwers consistently fell within the defined affordance space. This finding was not a function of throwers consistently using one particular solution. Manipulations of contextual conditions that shaped the affordance space (target distance and orientation) were associated with changes in movement solutions. The results of this study are consistent with the idea that individuals perceive affordances and control their actions based on them.

The work just described illustrates how affordances can refer to the action system of an individual performing the task and provide resources for action selection. The affordance of throwing resides in a space (a manifold) defined by three functionally relevant parameters of the dynamics of throwing and is defined in intrinsic, action-relevant units that fall directly out of the task-dynamical analysis. Therefore, affordances are properties that can in principle guide both learning and real-time action selection and execution after learning, without resorting to complex computations and representations.

6 Can Affordance-Based Control *Really* Substitute for Complex Cognition?

One might argue that the case of throwing is not strong enough evidence that perception of affordances can substitute for the complex computational processes implicated by the information-processing approach to motor behavior. A better test case would require a "representation hungry" problem (Clark 1997; Clark and Toribio 1994), one that supposedly cannot be solved with only ongoing, available information to perceptual systems. A paradigmatic example of a representation-hungry problem is anticipation of future states. Computational approaches have postulated internal models to explain anticipation (e.g., Miall and Wolpert 1996). However, research shows that there is an alternative to appealing to such computational-representational structures and processes. With the right kind of information, an individual can be coupled to her task environment in a way that supports behavior about forthcoming events without explicit prediction (McBeath, Shaffer, and Kaiser 1995; McLeod and Dienes 1996; Oudejans et al. 1996; Peper et al. 1994; Zhao and Warren 2015). This idea can be illustrated with a paradigmatic example from sports, the outfielder problem: How does the outfielder get to the right place at the right time?

For this particular problem, the ball-in-flight is the relevant aspect of the outfielder's environment. One way for the outfielder to catch the ball is to explicitly compute where and when the ball will land and select the speed and direction of locomotion to arrive at the correct location and time. This requires neural implementation of the equations of parabolic motion and a set of internalized statements of facts about the environment (the size, mass, and shape of the ball, air resistance, initial position and velocity, etc.). The solutions, therefore, resort to very complex cognitive processes of computation over representations, whether the calculations are explicit or implicit. The ecological alternative assumes the use of on-line information that specifies stable relations between the outfielder and the ball in the present that, if sustained, will direct the outfielder to the right place at the right time—in other words, information about ball *catchability* in the immediate future. This information must point to action strategies that result in successful performance. Two candidate information-based strategies have been delineated: run so as to cancel optical acceleration (McLeod and Dienes 1996; Oudejans et al. 1996) and run so as to create a linear optical trajectory (McBeath, Shaffer, and Kaiser 1995). A fly ball affords catching to actors with the set of skills to execute these strategies. Both strategies can be traced back to Chapman's nonanalytic strategy for catching a baseball (Chapman 1968).

The two identified strategies are competing hypotheses. However, they share a feature that is crucial to the argument that information-based control can *really* substitute for complex cognition: the actions of the outfielder trying to catch a ball creates optical information about her relation to the ball. If a particular relation is achieved and sustained, the outfielder will end up at the right place and time to catch the ball. The strategies presented suggest that acting in the present so as to stabilize a particular relation specified by ongoing information (either optical acceleration or optical trajectory) will result in successful ball catching at a future time. No explicit modeling or computation is required. Therefore, complex solutions to problems that seem to require representations might be greatly simplified by capitalizing on regularities that emerge as an individual actively engages with the environment in which she is embedded.

At this juncture, we hope to have provided evidence that explanations in terms of complex computational processes implicated by the information-processing approach can be greatly simplified if we consider the constitutive role of perception and action in intention formation and action execution. We now turn our attention to the implications of this understanding to the design of interventions to promote skill learning.

7 Skill Learning: Traditional Model of Practice

One of the primary tasks of coaches and rehabilitation professionals is to facilitate skill learning. The traditional model of practice to achieve this challenge was developed based on the information-processing approach to motor behavior, and in particular the motor programing theories proposed in the 1960s and 1970s (Keele 1968; Schmidt 1975). The most influential of these theories attributed skilled performance to (a) a generalized motor program whose charge was to specify a general, abstract movement solution to a particular class of tasks, and (b) motor schemas whose charge was to parameterize the solution according to extant conditions (Schmidt 1975). Accordingly, skill learning was defined as the process of acquiring (a) and (b) (Schmidt 1975). Traditional models of practice were, therefore, designed to facilitate this process. In particular, to facilitate acquisition of (a), instructors prescribe and demonstrate an idealized movement solution for the to-be-learned skill. To facilitate acquisition of (b), instructors create opportunities for learners to practice the prescribed movement solution under various task conditions with knowledge of results. This model of practice has been guided by results of research in the area of motor behavior and cognition designed to determine, for instance, the best way to structure practice (e.g., random or blocked) and/or the optimal scheduling for providing knowledge of results (Schmidt 1991; Schmidt and Young 1991). The findings of this research program continue to be applied in sport and rehabilitation settings to promote skill learning (Durham et al. 2009; Porter, Wu, and Partridge 2010). But is this a justifiable approach?

To answer this question, we consider a key feature of such a practice model. It requires an internal focus of attention by the learner. That is, an explicit focus on the prescribed movement form (or body movements). Can this be considered best practice in promoting skill learning?

8 The Evidence: Is There a Case for Promoting Internal Focus of Attention?

The evidence is overwhelming that models of training that promote an internal focus of attention during learning cannot be considered best practice, at least not in the general case. First, motor skills that are acquired explicitly tend to be less resilient if the individual is under either psychological (Beilock and Carr 2001; Gray 2004) or physiological fatigue (Poolton, Masters, and Maxwell 2007). Skills also tend to be less robust when a fast response is required (Turner and Fischler 1993). On the other hand, studies have shown that promoting an external focus of attention results in greater movement effectiveness in a wide range of tasks and contextual conditions (see Wulf 2013; Wulf and Prinz 2001, for reviews). For example, when soccer players were given the instruction to set a goal for the task of dribbling a ball around cones, those who chose a goal requiring an internal focus of attention, such as optimal dribbling technique, performed more slowly than those who set a goal requiring an external focus of attention, such as maintaining the position of the ball in relation to the cones (Jackson, Ashford, and Norsworthy 2006). Promoting an external focus of attention improves not only movement effectiveness but also movement efficiency. Examples include production of greater force magnitudes for a particular level of muscle activation (Wulf and Dufek 2009), greater muscular resistance against fatigue (Porter, Wu, and Partridge 2010), greater speed (Fasoli et al. 2002), and more efficient muscular coordination patterns (Lohse and Sherwood 2011).

The traditional model of practice to promote skill learning cannot be sustained based on the available evidence just reviewed. Training instructions should promote an external attentional focus on relevant components of the task environment and not on body movements. This evidence should inform the development of new, more effective models of practice. The particulars of these new models are not, however, fully determined by the evidence. What is the most effective means to promote an external focus? To answer this question, we must evaluate the available evidence, which requires reference to theory. Particularly relevant in this case are theories of motor behavior such as the ones just described. Different theories might support different interpretations of the evidence, which in turn lead to qualitatively different answers to the question just posed. The consequence is that qualitatively different training strategies may emerge. The effectiveness of new strategies should, of course, be verified by appropriate scientific methods before judicious application can be warranted.

9 Analyzing Evidence through the Prism of Theory: Explaining the Advantage of an External Focus of Attention

Wulf and Prinz (2001) articulated the "constrained action hypothesis" to explain higher gains in movement effectiveness and efficiency with an external focus of attention. Their explanation states that when an individual practices a skill with an internal focus of attention, she explicitly constrains the motor system in ways that disrupt "automatic processing." Directing attention to the effects of the movement in the task environment, in contrast, allows the more automatic and unconscious processes to operate, and performance improves. The conscious and automatic processes described in that hypothesis were not clearly defined, however. If different theories provide different definitions of those processes, then they might lead to very different kinds of learning protocols and different instructions to promote an external focus of attention. This is precisely the case we will illustrate here. Ecological and information-processing approaches to motor behavior have very different views on what this "automatic processing" is. We briefly recap such views and then close the chapter by showing that these different views result in very different ways of using visual feedback as a means to promote skill learning.

The information-processing approach makes a distinction between controlled and automatic processes (Shiffrin and Schneider 1977). Novel or difficult tasks require explicit attention and cognitive control, which taxes working memory, which has long been thought to be limited to approximately seven pieces of information at a time (Miller 1956). Practice can lead multiple pieces of information or motor instructions to be neutrally implemented as a single chunk. For example, learning to drive a car with a manual transmission requires careful attention to a sequence of actions, something like "release gas pedal, while almost simultaneously pressing clutch, then move gear stick, then release clutch, while almost simultaneously pressing gas pedal." After significant practice, this now-automatic sequence of events can become a single chunk "shift," which takes up much less working memory. This provides a possible explanation for the performance deficits caused by an internal focus of attention: focusing on the components of an automatic process can break the chunk into parts, which increases cognitive load and hurts performance (Rosenbaum, Kenny, and Derr 1983; Sakai, Kitaguchi, and Hikosaka 2003).

The ecological approach would equate automatic processing with the (self-ordering) dynamics promoted by the informational coupling of an individual's movements with the relevant aspects of the environment supporting task performance. When learning a new skill, individuals actively engage with their environments and discover stable relations with it that support task performance. These actor-environment relations, specified by simple informational variables, select the movement patterns that created them (Kelso and Fuchs 2016). Therefore, it makes sense that focusing on body movements would disrupt this process, because the information that directs the selection of movement patterns is in the task environment. Consider the case of the outfielder running to catch a fly ball. If she focuses on her body movements, she might not be able to couple her running to the ball's trajectory in a way that will lead her to the right place and time to intercept the ball. An ecological approach to learning would, therefore, naturally lean toward promoting an external focus of attention.[2] In the following section we discuss how the two different views are related to different motor learning strategies by considering different ways of using visual feedback to promote "implicit" learning of biomechanically efficient movement form.

10 Theory-Inspired Strategies to Promote Skill Learning: Providing Implicit "Instructions" through Visual Displays

Teaching proper form during sport maneuvers is the goal of sport coaches and rehabilitation professionals because of the increased risk of injury associated with less efficient movement solutions. For example, increased risk of anterior cruciate ligament (ACL) injury has been associated with employment of kinetic and kinematic patterns that increase stresses to the ACL, such as large amplitudes of knee valgus characterized by inward movement of the knees (Boden et al. 2000; Krosshaug et al. 2007; Olsen et al. 2004). Injury to this ligament has devastating consequences, including limited function, reduced levels of physical activity, and the development of disabling secondary knee conditions such as osteoarthritis (Barenius et al. 2014; Engström et al. 1990; Gottlob and Baker Jr. 2000; Gottlob et al. 1999; Kessler et al. 2008; Lohmander et al. 2004; Myer et al. 2014; Von Porat, Roos, and Roos 2004). Recovering from ACL injury is challenging, despite advances in surgical and rehabilitation techniques. Therefore, prevention is essential. Prevention typically involves efforts to improve movement form to reduce biomechanical risk factors (Hewett, Ford, and Myer 2006; Yoo et al. 2010).

Most interventions designed to facilitate optimal form still promote an internal focus of attention, despite the evidence and perhaps because of lack of other available options. For instance, there are a number of ACL injury prevention programs using explicit instructions regarding desired landing positions by emphasizing proper alignment of the hip, knee, and ankle (Di Stasi, Myer, and Hewett 2013; Myer, Brent, et al. 2008; Myer, Chu, et al. 2008; Myer et al. 2011; Myer et al. 2005; Paterno et al. 2004). More recently, there has been a push for the development of alternative strategies because of the demonstrated negative consequences of an internal focus of attention. Particularly relevant is the reduced resilience of motor skills learned explicitly in the context of higher physiological and psychological stress during competition (Beilock and Carr 2001; Poolton, Masters, and Maxwell 2007). The expectation is that movement form will suffer more in stressful game situations when it has been taught explicitly during practice, which might explain the limited success of prevention programs in reducing the incidence of ACL injury over time (Benjaminse and Otten 2011).

As implicit learning has proven to be effective in improving movement effectiveness (Wulf 2013), researchers in the area of sport medicine have hypothesized that it might also be effective in modifying the biomechanical features of movement that have been related to increased risk of injury (Benjaminse and Otten 2011; Kiefer et al. 2015). The challenging question is how to promote movement solutions that are biomechanically efficient without explicit instruction. Two different strategies, related to the two different theoretical views on the processes supporting action selection, have been proposed to prevent ACL injury and are presented here.

10.1 Information-Processing-Inspired Strategy: Action Imitation through Video Overlay

The information-processing approach to motor behavior espouses the idea that computational processes select and drive the execution of movement solutions for task performance. If this is the case, then learning might be facilitated by training methods that implicitly prime the neural mechanisms that instantiate these processes. There is evidence that the same visuomotor neurons (called mirror neurons) fire when an action is performed and when a similar or identical action is passively observed (Fadiga et al. 1995; Lotze et al. 1999). That is, observation of a particular action activates neural mechanisms involved in producing it. Therefore, action observation might be a good strategy to prime neural circuitries supporting effective and efficient movement solutions for task performance without the need for explicit instructions about the movement solutions themselves.

The empirical findings about neural activation during action observation inspired the proposition of a new general method for prevention of ACL injury that is consistent with the information-processing approach: action imitation through video overlay (Benjaminse et al. 2015; Benjaminse and Otten 2011; Gokeler et al. 2013). Essentially, the learner attempts to imitate a model producing biomechanically ideal movement solutions during training of risky sport maneuvers. To facilitate that, athletes receive visual feedback about the position of their body and that of a model. In particular, the learner sees in a visual display the contour of the model's body ("goal pattern") overlaid with the contour of her own body. The learner quite literally "steps into" a template of a gender- and size-matched model on the screen. The contour of the model works as a target and the only instruction is to replicate the model's movement as closely as possible. Of notice is the fact that learners still have to focus on producing a very complex contour—the visual feedback is as complex as the to-be-acquired pattern. This means that they have to potentially attend to many parameters at the same time. There is evidence that individuals have a hard time correcting more than three movement parameters at a time when employing an internal focus of attention (see review of biofeedback technology by Shull et al. 2014). Therefore, this might limit the success of the approach. The hope, however, is that shifting the learner's attention to the visual display and away from her own body movements will activate neural mechanisms that support the selection and execution of sought-after movement solution. This practice model is built on the assumption that biomechanically efficient movement solutions are embodied in neural mechanisms that can be "awakened" and reinforced through action imitation. The efficacy of this approach in optimizing movement patterns and preventing ACL injury still needs to be tested. In any case, it demonstrates the benefit of analyzing evidence in light of theory for the development and application of new and existing technologies to support skill learning.

10.2 A Strategy Inspired by the Radically Embodied-Embedded Ecological Approach: Augmented Neuromuscular Feedback

According to the ecological approach, expertise follows from our ability to discover movement solutions, in terms of low-dimensional patterns of stimulation that emerge in the context of task performance. Any strategy for learning inspired by the ecological approach, therefore, starts with the assumption that giving explicit, body-focused movement solutions to the learner for a particular task does not help them become experts in it. Instead, practice instructions should provide task-appropriate problems that encourage the learner to discover the solutions. Strategies to improve movement efficiency inspired by the ecological approach will, therefore, necessarily look very different from those inspired by the information-processing approach.

A model of training inspired by the ecological approach should foster skill learning by promoting sensitivity to information about the affordance space that supports task performance. Of relevance for present purposes is the fact that the affordance space for a particular task (e.g., landing from a jump) contains the entire set of movement solutions that leads to successful performance, including the ones that increase the risk of injury. For example, success in landing is determined by the ability to generate force to counteract downward acceleration of the center of mass. This can be done successfully using large magnitudes of trunk lean and knee valgus, despite the fact that these solutions increase stress on the ACL. There is no question that athletes usually are able to successfully perform sport maneuvers. Thus, to prevent ACL injury, attunement to information about their affordance spaces is not sufficient. The challenge is to design a training method to push experts to regions of the space that reduce their risk of exceeding biomechanical tolerance for sustaining an injury.

Augmented neuromuscular feedback (Kiefer et al. 2015) is a strategy, consistent with this logic, that has been conceptualized to promote biomechanically efficient movement patterns. The idea is to create implicit visual feedback during task performance about key biomechanical parameters characterizing safe movement solutions. What these parameters are will depend on the type of task and the type of injury to be prevented. This can be done by coupling the learner's movements to shapes in a visual display and relating the sought-after biomechanically efficient solution to an easily identifiable goal shape. The idea is to artificially create easily detectable information in the environment (e.g., in a visual display) about the portion of the affordance space that should drive action selection and execution. The instructions to the learner are not to simply imitate a pattern. Instead, the instruction identifies a perceptual goal that is simpler than the movement solution, per se: perform the task (squat, jump, etc.) so as to create a simple shape in the stimulus, for instance a rectangle. Biomechanically efficient solutions naturally emerge if learners achieve the goal shape; if they do so repeatedly, over the course of practice through mechanisms of implicit learning, then the learners may develop robust movement patterns that protect them from injury when transfer to the performance environment occurs.

Normally, a given action reliably produces a nonarbitrary perceptual outcome. However, the implementation of the proposed training strategy requires manipulation of the natural action-perception relation in artificial feedback displays. This can be done using motion-capture data, processed in near real time, to generate the display of visual images on a screen or portable augmented-reality display. Using that technological approach, a desired movement pattern—however complex in terms of segmental motion, kinetics, or joint rotations—can be mathematically transformed into a simple visual feedback pattern. Individuals can learn difficult movements in terms of the simplified visual pattern. In other words, they can implicitly discover the sought-after biomechanically efficient movement solutions through their attempts to create the desired, low-dimensional visual feedback. The required knowledge is "off-loaded" to the visual display. That is a prime example of how perception and action can substitute for complex cognition.

The power of the proposed approach to prevent ACL injury is gained through the abstract relation between movement patterns and visual feedback. Pointedly, the visual display does not showcase the to-be-acquired movement patterns themselves. By capturing the high-dimensional patterns in a perceptually available low-dimensional shape, the proposed augmented neuromuscular feedback has the potential to truly simplify movement control. This approach finds support in research showing that extremely difficult patterns can be learned if they are tied to simple perceptual outcomes. For example, it is nearly impossible to perform 4:3 bimanual coordination (the right hand completes four cycles of a circular movement while the left hand completes three cycles at the same time) while subjects view their hand movements directly. Yet this pattern is easily achieved when subjects cannot see their hands and instead are tasked with controlling the motion of two virtual feedback dots, where each dot is tied to the motion of one hand but the dots' movements are mathematically transformed so that a successful 4:3 hand pattern makes the dots appear to move synchronously in a 1:1, phase- and frequency-locked pattern (Mechsner et al. 2001). When subjects in that protocol are instructed to move their hands to externally focus on the coordination of the dots in a 1:1 pattern in the display instead of internally focus on their actual hand movements, a previously nearly impossible 4:3 movement pattern becomes relatively easy to master. In this case, the movement was learned implicitly using "knowledge" off-loaded to the task environment (Brenner and Smeets 2011; Shea et al. 2001). This type of motor learning is fast, robust, may improve retention, and leads to excellent transfer as demonstrated in prior studies employing this feedback principle (Fernandez and Bootsma 2008; Fowler and Turvey 1978; Kovacs, Buchanan, and Shea 2008; Kovacs, Buchanan, and Shea 2009; Mechsner 2004; Pawlak and Vicente 1996; Wang et al. 2013).

That the motor learning benefits of mapping movement variables onto simple feedback extend to learning complex, whole-body, closed-chain movement tasks is well supported (cf. Faugloire et al. 2005; Varoqui et al. 2011). In the experiment of Faulgoire and colleagues, subjects were tasked with in-phase or 180º anti-phase coordination of rhythmic rotations of the lower leg and trunk about the ankle and hip joints, respectively. Rather than being instructed explicitly to perform those coordination patterns, subjects were simply instructed to view a real-time feedback display and move the body so as to create either a circle or downward-sloping line. The feedback was, unbeknownst to subjects, an angle-angle diagram (ankle vs. hip joint rotations). In the joint angle space, a circle corresponded to in-phase and a diagonal line to anti-phase coordination. Subjects quickly learned to produce ankle-hip coordination patterns by an external attentional focus on "controlling" the desired shapes in the feedback display. Those who had this feedback available produced more stable postural coordination faster than those who did not. Moreover, when stroke patients performed this task as a balance intervention they showed long-lasting improvements in balance performance (Varoqui et al. 2011).

The proposed augmented neuromuscular feedback utilizes well-established visual feedback strategies to promote efficient, rapid, and robust learning of complex movements. However, the effectiveness of this form of training in promoting biomechanically efficient movement solutions and injury prevention also requires empirical support. Studies are under way to test it. The description of the training strategy is sufficient to indicate that analyzing evidence through the prism of a radically embodied, embedded account to motor behavior can lead to innovative and potentially transformative models of practice to promote skill learning. Augmented neuromuscular feedback is but one example. The key to transformative practice, in our view, is in the logic behind it: capitalizing on information revealed as an individual engages with her task environment to promote emergence of effective and efficient movement solutions.

11 Conclusion

There is no question that the design of new strategies to promote skill learning should be based on available empirical evidence. Less obvious is the idea presented above that advancing new models of practice and the development, or leveraging, of technology to support it could greatly benefit from analyses of empirical evidence in the light of theory. There are at least two benefits of explicitly tying the new training strategies proposed to theory. First, it promotes a rational, logical process for deriving new hypotheses from available evidence that has a greater chance to promote truly innovative and transformative interventions than does commonsense thinking or coaching lore. Second, scientific studies designed to test the effects of new forms of interventions on skill learning can provide an empirical basis that concurrently informs practice and furthers the theoretical understanding of motor behavior and learning. As this understanding develops, new propositions arise, and this cyclical process allows for more effective cross-fertilization between theory and practice.

In this chapter, two qualitatively different strategies were proposed to promote learning of biomechanically efficient movement solutions with the overarching goal of preventing ACL rupture, a serious sport injury. These strategies were derived from the analysis of the same empirical evidence (the benefit of an external focus of attention) through the prism of two different theoretical views on the processes supporting action selection. The prism provided by the information-processing approach led to a method of training aimed at priming the complex brain mechanisms involved in the production of the desired movement solutions: action imitation using video overlay. The idea of imitating a model is not new. The innovation refers to how the new technology allows the learner to shift her focus of attention to a visual display in the task environment and away from her own body movements, which is expected to facilitate learning. The prism provided by the ecological approach led to a method that encapsulates the sought-after movement solutions onto simple perceptual forms projected onto the task environment, trading perception and action for complex cognition. By focusing on creating and sustaining simple forms on a visual display, learners can implicitly discover and produce biomechanically efficient movement solutions without any explicit knowledge about the mapping between visual feedback and body movements. The training method promoted by the ecological approach is innovative in all of its aspects, from the logic behind it to the technology involved. If the effectiveness of this training in preventing ACL injury is verified by appropriate scientific studies, it can truly transform models of practice in the field of sport medicine.

Notes

1. In this chapter, we contrast an ecological approach to motor behavior with an information-processing approach. Another contrast, one we do not make here, could be drawn between ecological and enactive approaches. The relationship between these two approaches is one of great current interest. One of us has written about this in the past (Chemero 2009; Chemero 2012). We know of two conferences that were devoted to this relationship in 2016 alone ("Moving Cognition beyond Its Basic Ecology," University of Antwerp, May 2016; "Pluralism in the Cognitive Sciences," University College Dublin, June 2016). We cannot settle the issue in this chapter. That said, we think that although the philosophical commitments of the ecological and enactive approaches are quite different, their relationships to scientific practice and data are very similar. That is, although there are disagreements, they are "merely philosophical." We believe that enactive movement scientists will endorse the models and interventions we discuss in what follows.

2. Note that this is an example of the philosophical differences between the enactive and ecological approaches. Enactive theorists tend toward an idealist metaphysics, which could make them uncomfortable with the distinction between internal focus of attention and external focus of attention (e.g., Thompson 2007). Ecological theorists embrace a realist metaphysics and do not feel this discomfort. This is a genuine philosophical disagreement. That said, enactivists should be just as unhappy with what we (following the jargon of the literature) call "internal focus of attention" as we are, and should prefer what we (again, following the motor control literature) call "external focus of attention," even if they do not like these terms.

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