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18 Embodied cognition

From the playing field to the classroom

Carly Kontra, Neil B. Albert and Sian L. Beilock

Experience acting in the world is ubiquitous, and thus we may sometimes take for granted the profound effect it has on our perception of the world around us. Consider for a moment simple everyday actions such as reaching for and grasping objects. As an infant develops the necessary skill to perform these actions, his or her ability to interpret others' movement in a social context develops too (Woodward, 2009). Now consider a world-class athlete who spends many thousands of hours practising a set of skills (say, a jump shot in basketball or a 3-foot putt in golf). The process of accumulating a lot of specific motor experience, such as the practice needed to acquire athletic or musical expertise, can have a sizeable effect on both brain structure and function. Moreover, over time, practice changes the way our brain interprets and responds to relevant stimuli in the environment. Expert performers (e.g. athletes, musicians, dancers) represent the extreme of accumulated specific action experience and have thus been an important focus for the study of practice-related neural and cognitive changes. They are also an integral piece of the investigation into how people's action experience carries implications beyond their own performance, altering how they perceive the world around them.

In the current chapter we focus on structural and functional neural changes that accompany specific sensory and motor (sensorimotor) experience. Furthermore, we consider the effects that experience acting in the world can have on the perception of others' actions. The idea that sensorimotor experience impacts how we perceive information – even when we have no intention to act – begs the investigation of other situations in which action experience might affect cognition. In the final section of this chapter, we discuss some of the varied ways in which action impacts high-level cognitive activities. We discuss the potential for use of specific sensorimotor experience to drive learning within the realm of education, using literatures relating to embodied cognition and expertise in motor skills as a springboard. In particular, we explore how we might leverage sensorimotor learning to deepen comprehension of action-related concepts in the classroom.

Practice-related changes in neural structure and function

Within his model of expertise, Ericsson argues that deliberate practice produces physiological changes that are the building blocks of expertise (Ericsson, Krampe

& Tesch-Römer, 1993; Ward, Hodges, Starkes & Williams, 2007). These physiological changes most certainly occur in the body (e.g. muscles develop mass, speed improves), but they are seen in the brain as well. Neural changes underlying performance are thought to separate experts from less skilled individuals. These changes affect how the brain supports exceptional performance, and can be borne out in brain structure and/or function.

The classic example of structural changes associated with experience is the case of London cab drivers. London cab drivers develop extensive knowledge of the intricate metropolitan streets and how to navigate them ('The Knowledge' takes years of training and is a requirement for city taxi licensing). Maguire et al. (2000) showed that the posterior hippocampus, a cortical area important for navigating and recalling complex routes, is enlarged in London cabbies compared with non-drivers. The more convincing finding in connecting the role of practice with neural change is the significant positive correlation between the size of a cab driver's posterior hippocampus and the number of years spent behind the wheel. The longer a London cab driver has been on the streets (the more experience accumulated), the larger the part of his hippocampus involved in successfully finding a route becomes (Maguire et al., 2000). Similarly, mastering the art of juggling has been found to be associated with changes in grey matter density. Draganski et al. (2004) found that, after several months of practice at juggling, participants showed an increase in grey matter (where cell bodies of neurons are housed) density in areas of the brain involved with motion perception. This phenomenon generally indicates greater communication among neurons. When participants stopped their intensive juggling practice, density in those motion perception regions decreased; plasticity in neural structure relates to sensorimotor experience over time.

Practice-related effects have been studied extensively in musicians as well. One advantage of studying musical expertise is that experiments testing the abilities of musicians can independently focus on sensory or motor skill, and this level of control has led to some interesting observations. One remarkable sensory skill is absolute or perfect pitch, which is associated with early musical (e.g. piano, violin) training. Absolute pitch – the ability to name the exact note one hears, regardless of changes in other factors that typically affect pitch perception – is associated with an increased engagement of dorsolateral pre-frontal cortex during pitch discrimination tasks (Zatorre, Perry, Beckett, Westbury & Evans, 1998). This pattern of neural functioning goes hand-in-hand with marked changes in anatomical connections within the auditory system. Specifically, people with absolute pitch show greater connectivity between the primary auditory cortex and other brain regions that support the processing of sounds (Loui, Li, Hohmann & Schlaug, 2011). The relationship between early musical training and the attainment of absolute pitch suggests that absolute pitch is not simply an innate sensory skill, but one that is attained through specific (in this case, early) sensorimotor experience (for a review, see Münte, Altenmüller & Jäncke, 2002).

Numerous other researchers have substantiated expertise-related physiological and anatomical differences in musicians and connected these changes to training and experience (for a review, see Peretz & Zatorre, 2005). Using voxel-based morphometry, it has been demonstrated that higher-level brain areas with functions related to the motor system (e.g. Broca's area and superior parietal cortex) are better developed in expert musicians than in non-musicians (Gaser & Schlaug, 2003; Sluming, Brooks, Howard, Downes & Roberts, 2007). For instance, Gaser and Schlaug (2003) demonstrated that the extent of structural enrichment is related to measures of musical expertise and daily practice duration. More playing experience was related to increased grey matter density in primary motor and somatosensory areas, premotor areas, anterior superior parietal areas and the inferior temporal gyrus (Gaser & Schlaug, 2003).

The examples given above suggest that, across domains of expertise, the same deliberate sensorimotor practice that supports performance also invokes our inherent neural plasticity. Next we will move beyond the neural changes thought to support expert performance in order to investigate some of the less direct consequences of specialized action experience. These indirect consequences will be the impetus behind our proposed use of sensorimotor skill in an educational context. First, however, we introduce the theoretical framework that underlies this reasoning.

Embodied effects of sensorimotor experience on the observation of others' actions

Much of cognitive psychology regards the mind as an abstract information processor. However, work in the domain of embodied cognition strives to take into account the importance of interaction with one's environment; this tradition dates back to Gibson (1979), who espoused the evolutionary relevance of perception in service of action. Various theories of embodied cognition have emerged over the past few decades (see Barsalou, 1999; Niedenthal, 2007; Zwaan, 1999). Wilson (2002) summarized six prevalent viewpoints inherent in most concepts of embodied cognition, one of which she described as the idea that 'offline cognition is body-based' (p. 626). The brain inherently resides in a physical body, and is thus constantly exposed to perceptual information. During activation of mental representations that are allegedly abstract and decoupled from sensorimotor inputs, brain systems that evolved for perception and action may be co-opted to support cognition. In this way, sensorimotor resources can covertly affect high-level cognition even when there is no explicit intent to act. Support for this particular view of embodied cognition drives much of the research documented in the current chapter. Specifically, in terms of the investigation of action experience, these embodied views suggest that experience-dependent neural changes not only support the execution of actions, but play an important role in how expert performers understand and react to the actions of others.

How might one's experience performing a specific action change the neural activity underlying observation of that action? In one of the first studies to address this question, Calvo-Merino, Glaser, Grezes, Passingham and Haggard (2005) recruited participants with a range of experience performing classical ballet and capoeira (a Brazilian art form that combines elements of dance and martial arts). Calvo-Merino et al. used functional magnetic resonance imaging (fMRI) to study differences in neural activation when individuals watched actions in which they were skilled compared with actions in which they were not skilled. First, participants passively observed videos of the two movement styles in the scanner. Next, neural activity when participants observed their own dance style was compared with neural activity when they watched the other, unfamiliar dance style (e.g. ballet dancers watching ballet versus ballet dancers watching capoeira). When experts viewed the familiar versus unfamiliar movements, a network of brain regions thought to support both the observation and production of action elicited greater activation (e.g. bilateral activation in premotor cortex and intraparietal sulcus, right superior parietal lobe and left posterior superior temporal sulcus; Rizzolatti, Fogassi & Gallese, 2001).

In order to explore whether the specific experience of doing (as opposed to seeing) the actions within a domain was responsible for their effects, Calvo-Merino, Grèzes, Glaser, Passingham and Haggard (2006) examined neural activation in male and female ballet dancers. Classical ballet exemplifies codified movements that differ by gender. Because male and female ballet dancers train together, they have extensive experience seeing (but not doing) many gender-specific movements. Thus, ballet dancers represent an ideal group to test the relationships between motor experience, observation, and action perception. Calvo-Merino and colleagues found greater premotor, parietal, and cerebellar activity when dancers viewed movement from their own repertoire than movement performed by the opposite gender. Having previously produced specific actions affected the way the dancers subsequently perceived those actions, supporting the embodied hypothesis that systems involved in action production can also underlie action perception.

In another study with expert dancers, Cross, Hamilton and Grafton (2006) set out to 'build a motor simulation de novo' by training a specific set of movements and testing neural activity in response to seeing those movements before and after training. In doing so, Cross and colleagues provided some of the most compelling evidence to date for the experience-dependence of observational embodied effects. At initial testing, expert dancers' brain activity was recorded while they watched novel sequences of dance movements. Over the next 5 weeks, these dancers practised some of the novel sequences of movements but not others. After training, participants showed greater 'motor resonance', or neural re-instantiation of motor plans, when observing trained movement sequences than untrained movement sequences. In addition, neural activity was correlated with the dancers' ratings of their own ability to perform the various sequences. These data support the idea that our previous action experience impacts our ability to perceive the actions of others through a re-activation of some of the same sensorimotor brain areas we have used to act.

Finally, another example of the impact of doing (rather than seeing) on the observation of others' actions comes from work by Casile and Giese (2006). These researchers demonstrated that even a small amount of specific motor experience can enhance individuals' ability to make fine perceptual discriminations. Typically, human gait patterns are characterized by a phase difference of approximately 180° between the two opposite arms and the two opposite legs. Casile and Giese trained individuals to perform an unusual gait pattern: arm movements that matched a

phase difference of 270° (rather than the typical 180°). Participants were trained while blindfolded, and given only minimal verbal and haptic feedback from the experimenter. Before and after training, participants performed a visual discrimination task in which they were presented with consecutive pairs of point-light walkers. Participants were asked to determine whether the gait patterns of the point-light walkers were the same or different. Within each pair, one of the walker's gait patterns corresponded to a phase difference of 180°, 225° or 270°. The other point-light walker either matched the first exactly, or moved with a phase difference shifted slightly away from each of the three prototypes.

As one might expect, before motor training, participants performed at a high level of accuracy on the 180° discriminations, as these are the gait patterns most similar to what people see and do on a daily basis. In contrast, participants' discrimination ability was poor for the two unusual gait patterns (225° and 270°). After motor training, participants' performance on the 180° and 225° discriminations remained unchanged (relatively high and low accuracy, respectively). Importantly, discrimination performance significantly improved for the 270° displays: the gait pattern with which participants had been given sensorimotor experience. Moreover, the more accurately participants had learned to perform the 270° gait pattern during training, the better their post-test performance increase on the 270° discrimination trials. These data suggest a direct influence of learning a motor sequence on the ability to perceive slight variations in that sequence – an influence that does not depend on visual learning, as individuals were blindfolded during motor skill acquisition. Even brief motor training seems to have reorganized participants' representation of one specific gait pattern, integrating sensorimotor experience within that representation and thereby grounding visual discrimination performance in the sensorimotor systems of the brain.

One of the themes present in the above-mentioned findings is that areas of the brain typically associated with sensorimotor skill execution are recruited under circumstances where people are observing but not performing the action(s) in question. The results of these studies extend our understanding of the embodied theory that 'offline cognition is body-based' (Wilson, 2002, p. 626). When we observe others performing actions with which we are familiar, we experience increased motor resonance even when we have no intent to act (Aglioti, Cesari, Romani & Urgesi, 2008; Calvo-Merino et al., 2005, 2006; Cross et al., 2006). Moreover, the extent to which someone recruits sensorimotor processes during observation seems to be tightly linked to that individual's ability to perform the actions he or she is observing.

These embodied findings seem applicable to coaching methods; they suggest that, although observational training can sometimes be effective in terms of boosting performance, observation will be most effective when it integrates sensorimotor experience. Moreover, the idea that action experience changes not only domain-specific behavioural performance, but the neural basis of action observation, suggests that experience acting in the world may facilitate understanding of abstract conceptual information – for example, action-related language. At its core, this idea provides strong evidence for the potential value of athletic training far beyond the playing field. Whereas most arguments for physical education focus on benefits such as learning teamwork, maintaining cardiovascular health, learning to live a healthy and active lifestyle, and the expansion of executive function abilities, it may be the case that a breadth of sensorimotor experiences leaves students with a greater expanse of the brain available to support subsequent conceptual representation. If embodied representations can support higher-level conceptual processing, it stands to reason that this could be a useful framework for efforts toward educational interventions and improved achievement. In the next section, we explore the idea that the neural processes which typically underlie our ability to act also come to subserve our ability to understand.

Applying sensorimotor experience in the classroom

Work by Glenberg and colleagues (Glenberg, Brown & Levin, 2007; Glenberg, Gutierrez, Levin, Japuntich & Kaschak, 2004) presents evidence for the potential educational value of an embodied cognition framework. Glenberg et al. explored language comprehension in young children in both formal and informal learning environments. Students worked in action and non-action reading groups. In an action reading group, each student read a sentence aloud and then acted out the events of the sentence using objects mentioned in the text. In the non-action group, students simply read the sentence aloud and then repeated it. On a subsequent comprehension test, students who had acted out the sentences' events showed significantly greater understanding and retention than those who had read the sentences repeatedly (Glenberg et al., 2004, 2007). Sensorimotor experience with the sentence content enhanced students' understanding and, also importantly, their retention of the learned information.

Why would this sensorimotor experience be beneficial for understanding high-level concepts? One potential theory is that physical experience is beneficial merely because it serves to engage students with the activity in question. Students may devote more attention to the entire learning experience and thus understand and remember more content. However, from an embodied cognition perspective the more interesting claim is that students' experiences acting out the events in each sentence allowed them to call upon a rich set of sensorimotor experiences when they were later being tested for comprehension. Perhaps this second mechanism lies behind the action reading group's enhanced understanding and retention of the material. Support for the latter idea comes from related work out of our laboratory.

Beilock, Lyons, Mattarella-Micke, Nusbaum and Small (2008; see also Holt & Beilock, 2006) used a case of athletic expertise to test the transfer of embodied effects to language comprehension. Beilock et al. (2008) recruited expert and novice ice hockey players for a behavioural and neuroimaging study. In the scanner, participants passively listened to sentences depicting hockey-specific actions (e.g. 'The hockey player finished the stride') and everyday actions (e.g. 'The individual pushed the cart'). Later, all participants completed a comprehension test outside the scanner that gauged their understanding of the sentences they had heard.

The comprehension task involved the auditory presentation of each sentence (hockey-specific or everyday action) followed by the presentation of a picture (Figure 18.1). Participants were asked to judge whether the actor in the picture had been mentioned in the sentence. In some pictures, the actor performed the action described in the sentence; in some, the actor performed an action not mentioned in the sentence; and, in some, the actor pictured was not mentioned at all in the sentences (these were included as fillers). If participants comprehend the actions described in the sentences they hear, they should be faster to correctly identify a match between the actor in the picture and the actor mentioned in the sentence when that actor is pictured performing an action that matches the action described in the sentence (compared with when that actor is pictured performing an action that does not match the action described in the sentence).

As expected, all participants regardless of hockey experience performed well on the everyday action sentences. However, behavioural performance for the hockey-specific action sentences was correlated with hockey experience such that the experts exhibited greater comprehension than novices (see Beilock et al., 2008).

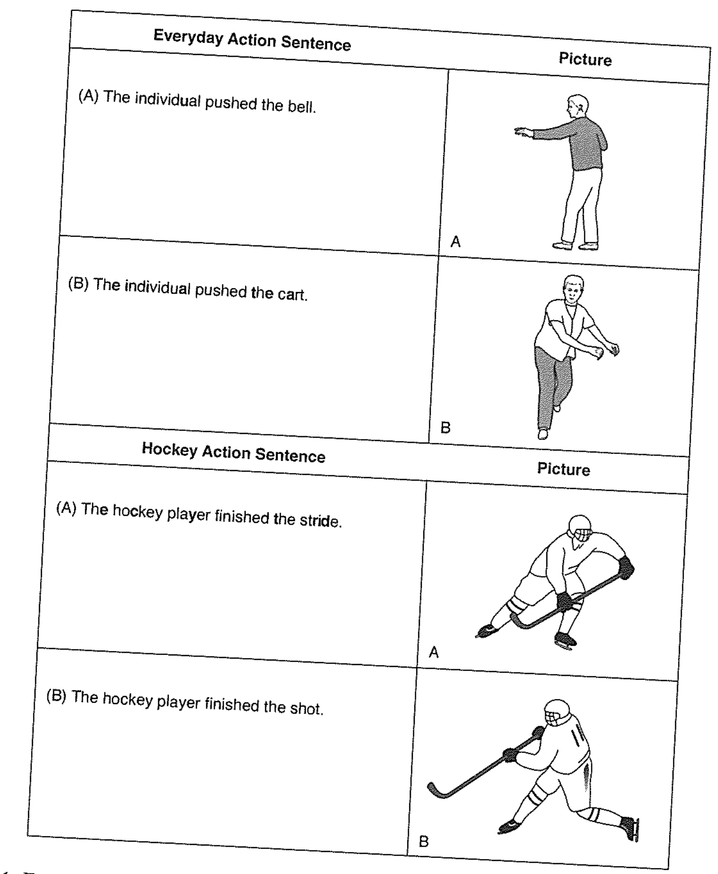

Figure 18.1 Example sentences and pictures presented during the comprehension task in Beilock et al. (2008). Adapted with permission.

Most interestingly, the neural data collected when individuals merely listened to the hockey action sentences explained the relationship between hockey experience and sentence comprehension. In particular, activity in the left dorsal premotor cortex (dPMc, Figure 18.2) fully mediated (or accounted for) the relationship between action experience and comprehension. The more extensive an individual's hockey experience, the greater the neural activation in left dPMc for hockey-specific language and the better an individual's hockey specific language comprehension. These data support the hypothesis that our understanding of language describing action is driven by experience-dependent activation of dPMc, a region thought to support the selection of well-learned action plans and procedural knowledge (Grafton, Fagg, & Arbib 1998; O'Shea, Sebastian, Boorman, Johansen-Berg & Rushworth, 2007; Toni et al., 2002).

This work with hockey players exemplifies how sensorimotor experience can lead to the recruitment of brain areas not typically associated with the cognitive task at hand (e.g. language processing). This recruitment was shown to be beneficial for comprehension of action language and probably explains why Glenberg et al. (2004, 2007) found improved story comprehension for children who had acted out the events in the stories in question. We propose here a theoretical leap in the

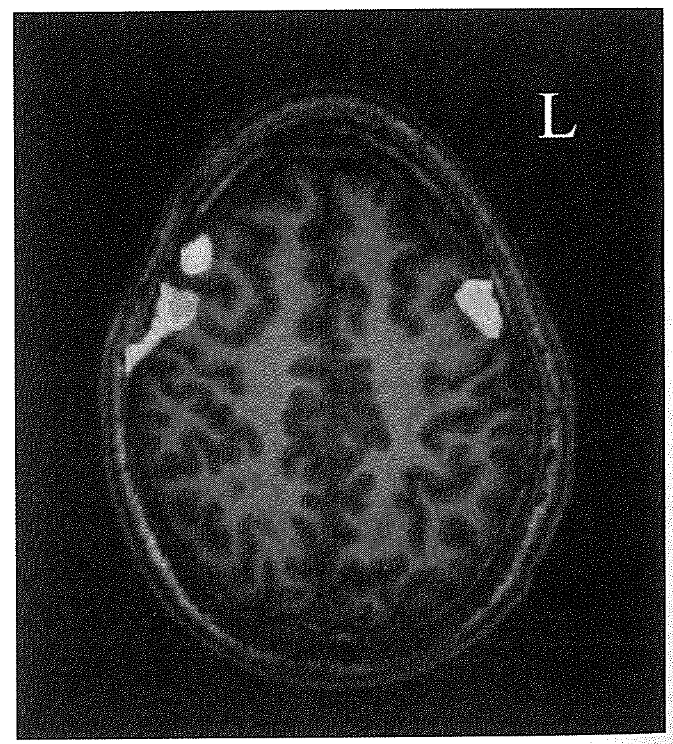

Figure 18.2 Visualization of dorsal premotor regions implicated in Beilock et al. (2008). Reprinted with permission.

application of this finding; namely, a place for specific sensorimotor experience to support learning in the classroom. Consider a college-level course in physics as an example. Introductory physics courses traditionally begin with topics in mechanics, and it is here that students first encounter the challenging concept of vector quantities such as velocity, force, torque and angular momentum. These quantities exhibit a salient relationship between concept and action, and lend themselves well to sensorimotor experiences in the classroom/laboratory environment during which the student takes on an active role.

Of course we do not mean to suggest that the general idea of learning from experience is a novel one. In fact, science education commonly includes a laboratory-based component built out of models of experiential learning (e.g. Kolb, 1984). However, these experiences can vary widely both in design and in execution. For instance, laboratory sessions are typically completed in small groups of students who will take a more or less active role. Even within the category of active laboratory experiences, activities can range from the observation of physical phenomena to the measurement of outcomes to the diagrammatical depiction of invisible physical forces. From the perspective of embodied cognition, one could argue that rich sensorimotor experience tightly linked to the concept in question will drive learning most effectively. This scenario predicts the formation of a representation in the student's sensorimotor system that will come to underlie his or her conceptual representation.

We have begun to test these predictions in the laboratory, using mechanical physics as a conceptual test-bed for other educational applications. Undergraduates at the University of Chicago who had no college-level physics experience participated in pairs. Each participant was randomly assigned to either the Action or the Observation group. During a 10-minute training session, participants felt (Action) and/or saw (Observation) a series of trials involving two bicycle wheels on an axle. The wheels were used to demonstrate various factors that change the angular momentum of a physical system, and thus affect torque when the wheels' axle is tilted through space (Figure 18.3). As Action participants tilted the axle of the spinning wheels, they felt a resistance that indicated the magnitude and direction of torque for each trial. Observation participants received visual information about the magnitude and direction of torque for each trial via a laser pointer mounted in the axle (see Kontra, Beilock & Fischer, in preparation).

Before and after training, participants completed a computerized torque judgment task (TJT) to assess comprehension. They were asked to compare videos of two avatars, each tilting a set of bicycle wheels on an axle just like the ones used during training. Factors such as the moment of inertia, angular speed, direction of spin and rate of tilt were varied from trial to trial. Participants had to determine which of the two avatars was experiencing more torque (or resistance), or alternatively if the two avatars were experiencing the same amount of torque.

The Action and Observation groups did not differ in accuracy on the pre-test TJT. However, at post-test the Action group showed a 10% improvement in performance above the Observation group. This improvement seems to have been driven mainly by increased comprehension of the concept of vector cancellation, or the

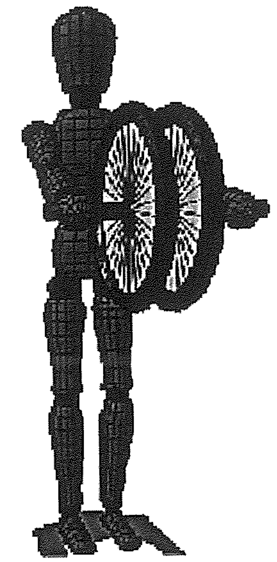

Figure 18.3 Schematic of an Action participant manipulating bicycle wheels on an axle.

idea that angular momentum and torque are vector quantities with both magnitude and direction and can therefore cancel and sum to zero. The Action participants seemed to be integrating their specific sensorimotor experience with the bicycle wheels with their subsequent performance on our physics comprehension task. After just 10 minutes of specific action experience linked to the concepts of torque and angular momentum, participants were better able to make judgments about the magnitude of torques within a physical system. [Within this work we are not yet able to parse the relative contributions of creating the torque (tilting the axle) and feeling the torque (experiencing resistance, or deflection of the axle, while tilting).] During post-test, Action participants may be relying on a re-instantiation of motor areas of the brain to support learning. We are currently testing this idea using fMRI.

These findings support the notion that, beyond implications for performance and the observation of others' actions, sensorimotor experience can impact high-level cognitive activities such as comprehension of action language or physics concepts. Although more work needs to be done in order to investigate which concepts will benefit most from sensorimotor training, and what aspects of sensorimotor experience are most effective in driving learning, our findings represent an exciting application of embodied cognition within the educational realm.

Summary and conclusions

We have discussed various examples of neural and behavioural evidence that demonstrate changes resulting from motor experience and the attainment of

skill expertise. As in the examples of navigational and musical expertise, experience changes the brain both in structure and in function. These changes carry implications for performance. However, beyond implications for performance within a domain, a hallmark of these experience-dependent changes is that offline cognition relating to the learned skills becomes body-based. Re-instantiation of previous sensorimotor experience can affect the perception of others' actions, as we saw above in the examples of ballet dancers and capoeira experts. Furthermore, because sensorimotor experience impacts perception by the recruitment of neural regions involved in action instantiation, it seems that motor experience can impact higher-level cognitive activities (e.g. language and physics comprehension) when one is merely thinking about the concepts in question. This idea carries strong educational implications.

In our opinion, recent work in the embodied cognition literature provides an avenue for investigation into methods of educational intervention. The theoretical framework we have discussed has already been shown to be influential in the realm of sensorimotor skill acquisition, as well as in providing a general neural mechanism for effects of expertise on action observation. Perhaps we can revisit decades of fascinating motor learning research with an eye toward driving educational improvement. There is considerable basic research to form the foundation of an applied agenda, and the time may be right to see those basic science efforts extended into an educational context.

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19 Especial skills

Generality and specificity in motor learning

Gavin Breslin, Richard A. Schmidt, and Timothy D. Lee

Introduction

In studies involving the performance of expert basketball players executing the set shot from different distances, Keetch, Schmidt, Lee, and Young (2005) found that success was negatively related to the distance of the shooter to the basket; as the distance from the basket increased, accuracy declined. This finding is not new, of course, as numerous principles of motor control predict this result (e.g., Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). However, a rather unexpected finding was that, when the shot was taken from one specific location 15 ft from the basket, performance was considerably more accurate than the accuracy predicted from surrounding locations (i.e., 9, 11, 13, 17, 19, and 21 ft).

Figure 19.1 contains a plot of the accuracy of set-shot performance (percentage correct shots) as a function of the distance from the basket. Individual regression analyses using the shortest three distances (9, 11, and 13 ft) and the longest three distances (17, 19, and 21 ft) yielded the line of best fit illustrated in Figure 19.1. The value predicted for the 15-ft shot was interpolated from these analyses. As represented in the figure, the actual performance at the 15-ft distance was considerably (and significantly) more proficient than performance predicted from the regression analyses.

Keetch et al. (2005) argued that there is a relatively simple explanation for this finding. As all basketball players know, the 15-ft. distance to the basket represents the free throw line (or foul line): the location from which a player may take an undefended set shot after being fouled during play (i.e., with no defensive player, almost always using a shot in which the feet do not leave the floor). Moreover, since "foul shots" occur frequently during a basketball game, and often play an important role in the outcome of a contest, there is usually considerable emphasis placed on taking foul shots during practice. During practice, these set shots are taken almost exclusively from the 15-ft distance, which is the same as during a game. Moreover, set shots are almost never taken in the regular flow of play (because the shot would be relatively easy to block). Thus, the set shot is a particular skill that is practiced with the intent of being used for one specific aspect of basketball play only: taking a foul shot.

The participants studied by Keetch et al. were basketball experts (collegiate-level players). So, during their skill development they had no doubt accumulated massive