

3 Mental Imagery and Implicit Memory

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INTRODUCTION

Alan Paivio's research had an enormous influence on the development of cognitive psychology. Using rigorous experimental methods, he showed that mental imagery plays a key role in human memory. The mountain of work he produced documented in detail his thesis that there are at least two ways to encode information, verbally and visually—and memory is enhanced when both of these types of codes are used (e.g., Paivio, 1971, 1986; see also Amit, Algom, Trope, & Liberman, Chapter 4, this volume).

Paivio focused on what has since been characterized as *explicit* memory: memory for facts and events that can be called to mind at will (see Schacter, 1987, 1996; Squire, 1992). However, much of what we know consists not of facts or events that we can consciously recollect (e.g., for many of us, the name of the lead singer of U2) but rather of ways to behave or tendencies to process information in certain ways in certain situations. We know how to drive, eat with a knife and fork, and maybe even how to bow correctly in Japan. Much of such knowledge is *implicit*: It cannot be voluntarily called to mind but rather is evoked by specific cues to guide our behavior (cf. Schacter, 1987, 1996).

We consider two closely related topics. First, we briefly review evidence that imagery can be used to access implicit information stored in memory. Next, we focus on the idea that imagery can be used to alter such stored information, which in turn can affect our later behavior.

USING IMAGERY TO ACCESS IMPLICIT MEMORIES

One of the remarkable aspects of mental imagery is that we can use it to access at least some aspects of implicit information stored in memory. By definition, such information cannot be retrieved directly, but we sometimes can access it indirectly—by noting how it affects our mental images. For example, when people are asked to imagine grasping an object, the time they take depends on exactly how they are asked to take hold of it. For instance, imagine seeing a hammer sitting on a table and reaching down, picking it up by the handle; compare this to when you imagine placing the back of your hand on the table and sliding your hand under the handle, grasping the hammer with your palm facing up; then compare this to when you reach down and pick it up only with your thumb and forefinger. You would take different amounts of time to simulate these behaviors, and the relative amounts of time would mirror the time you would take to perform the corresponding actual actions (e.g., Beilock & Lyons, Chapter 2, this volume; Decety & Stevens, Chapter 1, this volume; Frak, Paulignan, & Jeannerod, 2001; Jeannerod, 2001; Johnson, 2000; Parsons, 1994; Parsons & Fox, 1998; Sekiyama, 1982, 1983). The participants in these studies were not consciously aware of the biomechanical information they take into account when mentally simulating the actions any more than a seal solves differential equations when catching a ball on its nose.¹

Many sorts of studies have used mental imagery to tap into implicit information stored in memory. For example, in one study researchers asked participants to take part in two experiments (Decety, Jeannerod, & Prablanc, 1989). In the first experiment, participants were blindfolded and

asked to imagine walking a specific distance to a goal and to press a button when they arrived. In the second experiment, the participants actually walked that distance, and the time they took to reach the goal was recorded. In both imagined and actual walking, the greater the distance, the longer the participants took. Moreover, the participants took remarkably similar amounts of time to imagine walking as they required when actually walking. This finding nicely lines up with what we would expect based on the idea that imagery taps into implicit memories that control movements.

But, now we need to consider a wrinkle: In another experiment, these researchers asked the participants to imagine wearing a heavy backpack (25 kg) and to repeat the same two tasks. When mentally simulating this situation, they imagined that they would require more time to walk longer distances than they did when not wearing the backpack, but in fact when actually tested they walked as quickly as before (sans backpack). Apparently, the participants did not realize that they would simply expend more energy to keep up their previous pace with the heavy load (Decety et al., 1989; see also Decety, 1996). Thus, imagery is not a "royal road" to implicit memory. Rather, imagery also reflects our explicit expectations (e.g., that people walk slower with backpacks), which operate jointly with implicit knowledge to govern imagined scenarios.

Moreover, our images are only as good as the implicit information we have stored, even when that information may be relatively abstract. For situations in which we lack real-life experience (and thus lack the corresponding specific implicit information associated with those experiences), our imagery can be prone to flaws. Here is a particularly vivid example of how gaps in our implicit knowledge can lead imagery to go astray: Participants were asked to look at a picture of a tube wound into a spiral on the ground (looking a little like a coiled snake). They were asked to imagine a ball put in one end of the tube and then "shot out the other end at high speed." The participants were then asked to indicate the path they thought the ball would take when it flies out. McCloskey, Caramazza, and Green (1980; see also McCloskey & Kohl, 1983) found that many people believed that the ball would continue to fly along a curved path. In point of fact, in this situation a ball would continue along the tangent of the circle, in a straight line. Because we lack real-life experience with certain scenarios (e.g., projectiles exiting curved tubes), we use scenarios in which we do have real-life experience (e.g., projectiles exiting straight tubes) or knowledge of relatively abstract principles (presumably gleaned from such experiences) to simulate such events. The limits and biases of our everyday physical experiences and the generalizations we make from them often lead us to adopt incorrect views of physics (which may be one reason it took so many centuries for the correct principles to be discovered; Caramazza, McCloskey, & Green, 1981). These limits and biases of experience are reflected in limits and biases of our stored, implicit information, which form the basis for our occasionally faulty images.

In short, there is good evidence that imagery is sensitive to implicit information stored in memory. But, it is one thing to reflect the influence of such information and another to alter it. In the following section, we consider the role of imagery in actually entering new implicit information into memory. By "new," we include modifications of information that is already present in memory; we note that rarely is anything *entirely* new for an adult, but rearrangements of preexisting material nevertheless can produce representations that previously did not exist.

USING IMAGERY TO STORE IMPLICIT INFORMATION

An impressive body of evidence demonstrates that mental imagery can produce new implicit memories that help people to learn new activities. This evidence lies in the domain of mental practice. The key assumption underlying mental practice is that the representations stored in memory during such practice later can guide one to perform the corresponding actual activity.

IMAGERY AND MENTAL PRACTICE?

Mental practice hinges on visualizing oneself moving and imagining what it would feel like to move that way in space. Several types of imagery are involved in mental practice: Not only does one "see

oneself" perform an action (a visual image), but also one is aware of the spatial relations of objects and their parts (spatial images), the sounds associated with an action (auditory images), and the bodily sensations that accompany movements (kinesthetic images). Not only are the objects and their parts being visualized stored in memory but also the movements are governed by information stored in implicit memory (cf. Vieilledent, Kosslyn, Berthoz, & Giraudo, 2003).

Numerous experiments have shown that the content of imagery during mental practice affects later behavior. Consider a now-classic study of mental practice in golfing (Woolfolk, Parrish, & Murphy, 1985; see also Powell, 1973), which dramatically illustrated the role of imagery in mental practice. In this study, the researchers first asked college students to putt a ball into a hole, and an initial "putting score" was recorded. The researchers then sorted the participants into three groups (ensuring that the participants in each group had comparable levels of skill at the outset, but otherwise randomly assigning participants to groups) and gave different instructions for mental rehearsal to each group. The participants in one group were asked to visualize putting a golf ball right into the hole (this was the "positive imagery" group); those in a second group were asked to putt a golf ball so that it just missed the hole (the "negative imagery" group); and those in the final group (the control group) were simply asked to visualize putting with no specific instructions about how to visualize. Following mental practice, the participants putted again, and another score was recorded. The results were dramatic: After mental practice, the participants in the positive imagery group performed 30.4% better than they had initially. The participants unlucky enough to have been assigned to the negative imagery group actually got worse, now scoring 21.2% more poorly than they had initially. (This decreased performance could reflect poor motor programming, "imagined frustration," or a number of other possible factors.) Those in the control group got only a bit better (9.9%).

One can use mental practice right before actually performing or well in advance of performing the movement. David Hemery (1988) interviewed 63 of the world's top athletes and reported that some 80% relied on imagery to enhance performance (see also Suinn, 1985; Ungerleider & Golding, 1991). Such mental practice is not confined to sports but rather applies to all activities. For example, when tenor sax player Gerry Bergonzi toured with Dave Brubeck, he used mental practice while he was on airplanes. He was on the road so often that he did not have many other opportunities to practice—mental or otherwise (H. G. Cox, Jr., personal communication, September 2001). Mental practice is especially useful for one-shot or dangerous events, when one does not have the luxury of actually performing them numerous times or when actual practice is too dangerous (for reviews of the literature and classical theories of mental practice and relevant findings, see Feltz & Landers, 1983; Grouios, 1992a; Jones & Stuth, 1997; Romero & Silvestri, 1990; Rushall & Lippman, 1998; Suinn, 1997; and Taktek, 2004).

For example, consider how surgeons "practiced" prior to performing a grueling 33-hr operation to separate twins who were born joined at the tops of their heads (so that even parts of their brains had melded together). This was an extraordinarily difficult and complex operation. Not only did 60 people participate on the medical team, but the surgery involved many complex steps; at its conclusion, the twins had no skulls above their foreheads (their heads were described in one report as being like "egg cups"), and the surgeons had to remove tissue from the boys' thighs to create a membrane to cover their exposed brains. (The surgeons' plan was to build the rest of the skulls out of pieces of bone salvaged during the operation supplemented by bones from cadavers.) A key part of the preparation for this operation was mental practice:

"When I do a real operation, I play the videotape ahead of time in my mind," Dr. Shapiro said.

Dr. Sklar said, "We were discussing this imaginary videotape for a long time."

"I do the case in my head," said Dr. Maria Ortega, an anesthesiologist. "I must have done it 100 times. Every time, a problem would come up and I would find a solution and do it again. Every time I ran it in my head, it went faster. I'm sure everybody did the case 100 times."

By the day of the surgery, Dr. Ortega said: "I was excited. I was elated. I was so confident. We had planned and talked and beaten each other over the head and challenged each other. We were ready. It was like the big game. 'Yes! Yes! Send me out there, coach!'" (Grady, 2003, p. 33)

Another compelling example of real-life mental practice comes from the field of power line maintenance. Because the penalty for error in this profession is so high (e.g., electrocution), individuals who inspect and maintain power lines do not have the luxury of learning through trial and error. In many cases, their job requires an extraordinarily complex set of movements. For instance, some high-voltage cable inspectors are flown to high-power lines via a helicopter, navigate from the helicopter to the 100-foot-high cable (while wearing a mesh full-body "hot suit" that acts as a Faraday cage), then traverse the cable on their hands and knees looking for areas that need repair.² David Harding, a power lineman for National Grid, reports how he uses mental practice to prepare for his work:

I find I mentally practice a task in my head many times before I go up the pole and actually perform it. If I know what I'll be doing the next day I catch myself going over it in my head over and over again at home till I realize what I'm doing and I say to myself, "What the hell am I doing?" ... I do this even with tasks I've performed hundreds of times before. Even when I roll up on a motor vehicle broken pole accident with police and fire on scene and lights flashing everywhere, I still take a couple seconds to go over the pole in my head and think about how my rigging will change as I'm moving conductors. (D. Harding, personal communication, May 2007)

As fascinating—and even compelling—as such testimonials are, they count for little in science. Is there evidence that mentally practicing an activity leads people to learn new skills or to perform a familiar activity better? Researchers have studied the efficacy of mental practice in almost every conceivable sport, including table tennis (Lejeune, Decker, & Sanchez, 1994); martial arts (Park, 1993); diving (Grouios, 1992b); golf (McBride & Rothstein, 1979); horseback riding (Fischer, 1995); racquetball (Gray, 1990); foul shooting in basketball (Clark, 1960); soccer (Salmon, Hall, & Haslam, 1994); football (Fenker & Lambiotte, 1987); rugby (Evans, Jones, & Mullen, 2004); volleyball (Johnston, 1971); rowing (Barr & Hall, 1992); figure skating (Rodgers, Hall, & Buckolz, 1991); track and field (Ungerleider & Golding, 1991); marksmanship (Whetstone, 1993); softball (Calmels, Berthoumieux, & d'Arripe-Longueville, 2004); shot put (Gassner, 1997); gymnastics (Palmer, 1971); sit-ups (Kelsey, 1961); field hockey (Wiegardt, 1998); wrestling (Mills, Munroe, & Hall, 2000–2001); swimming (Yamamoto & Inomata, 1982); goaltending in ice hockey (McFadden, 1983); tennis (Rahahleh & Al-Khayyat, 2001); kayaking (Millard, Mahoney, & Wardrop, 2001); cricket (Gordon, Weinberg, & Jackson, 1994); tenpin bowling (Wollman, Hill, & Lipsitz, 1985); dart throwing (Mendoza & Wichman, 1978); and even weight lifting (Hale, 1982). Researchers have also considered the effects of mental practice in activities as diverse as playing a musical instrument (Theiler & Lippman, 1995), conducting an orchestra (Bird & Wilson, 1988), and landing an airplane (Prather, 1973). Finally, although scientists have yet to study the effect of mental rehearsal on the surgical separation of conjoined twins, they have demonstrated its benefit for training basic surgical skills (Sanders, Sadoski, Bramson, Wiprud, & van Walsum, 2004).

WHEN DOES MENTAL PRACTICE WORK?

With such a great variety of studies of so many different activities, it is not surprising that not all studies have reported effects of mental practice (Corbin, 1972; Richardson, 1967). However, the majority of studies clearly showed that mental practice does improve performance; in fact, mental practice is one of the few "performance-enhancing" activities that a committee of the National Academy of Science found to be effective (Druckman & Swets, 1988). Let us take a closer look at exactly when mental practice is effective.

Driskell, Copper, and Moran (1994) performed a meta-analysis of the results from every well-conducted study of mental practice (i.e., that relied only on mental practice, and not other manipulations such as relaxation, and that included a no-practice condition or group) they could find in the literature. Although their most fundamental conclusion was that mental practice is generally effective, they also identified five factors that explain why it does not always work or does not work as effectively as it does in other circumstances.

1. One cannot entirely substitute mental practice for actual practice. Even though mental practice is better than nothing, usually physical practice is still better. However, although this general conclusion is correct, it does not apply to each and every individual case. Several studies have reported that mental practice can be just as good as actual practice (see Richardson, 1967; Weinberg, 1982). Clearly, mental practice will increasingly approximate actual practice to the extent that one has accurate images (cf. Suinn, 1984, 1994). Thus, feedback from actual performance, which allows one to tune images appropriately, should be critical. And in fact, some studies have reported that mixing actual practice with mental practice is not only better than mental practice alone, but can actually be better than purely physical practice (e.g., Riley & Start, 1960; Stebbins, 1968; Trussell, 1952; Weinberg, 1982). This last finding has not always stood up well (Hird, Landers, Thomas, & Horan, 1991), but nevertheless mixing physical practice with mental practice should enhance the effects of mental practice.
2. The amount of benefit from mental practice depends on the activity. As expected if the result of mental practice is to store implicit information, one is more likely to benefit if the task has a large "cognitive" component. That is, mental practice is more effective when tasks (such as playing basketball) require one to search for, organize, compare, and contrast information, as well as to make evaluations and decisions. If the task simply requires exerting force, maintaining balance, or other sorts of muscular control, mental practice is not as effective. Nevertheless, mental practice is better than nothing even for such tasks.

This finding is not surprising, given that mental simulations help one to organize, compare, and contrast information and make evaluations and decisions. What may be surprising, however, is that mental practice is not a purely intellectual activity: It also affects strength and other more physical aspects of behavior. For example, researchers found that simply imagining moving the fingers improved muscle strength almost as much as isometric exercises (22% improvement from imagery vs. 30% from isometric exercises; Yue & Cole, 1992; see also Yue, Wilson, Cole, & Darling, 1996). This makes sense because we know that imagining that one is performing an action actually engages the parts of the brain that control the muscles themselves (Kosslyn, Thompson, Wraga, & Alpert, 2001; Wraga, Thompson, Alpert, & Kosslyn, 2003). By repeatedly engaging the motor control processes responsible for a specific finger movement, participants in this experiment were able to hone those processes and, as a result, increase actual muscle strength.³

Imagining that one is activating the muscles repeatedly could have at least three effects: (a) It could actually strengthen the appropriate muscles. In fact, researchers have shown that when people imagine performing an action, very much the same pattern of muscles twitch—in the same order—as are used during the real thing (for reviews, see Grèzes & Decety, 2001; Jeannerod, 2001; Jeannerod & Decety, 1995). This correspondence in muscle activity has been shown in a variety of sports, including skiing (Suinn, 1980), basketball, rowing, horseback riding, swimming, and water skiing (Bird, 1984). However, one probably will not strengthen the muscles much by doing this; after all, one activates them just below the level needed to produce an actual movement. (b) Feedback from the stimulated muscles might strengthen the motor program that triggers the muscles. This is the classic *psychoneuromuscular theory* (which has been credited variously to Carpenter, 1894; Jacobson, 1932; Washburn, 1916). However, mental practice works even when the relevant muscles are temporarily immobilized, which prevents them from sending pertinent signals back to the brain (Yue et al., 1996). In addition, paralyzed and nonparalyzed individuals show the same changes in brain activity during mental practice, suggesting that neuromuscular feedback is not vital for mental practice effects (Cramer, Orr, Cohen, & Lacourse, 2007). (c) The central programs that activate muscles may become more efficient simply through being used more often. Aside from explaining the aforementioned data from immobilized and paralyzed participants, this account best explains the shifts

in brain function associated with mental practice (e.g., Jackson, Lafleur, Malouin, Richards, & Doyon, 2003). Other possible mechanisms exist as well. For example, perhaps mental practice enhances strength by "giving yourself permission to go all the way."⁴ We often hold in reserve some strength, not allowing ourselves to exhaust all of our physical resources. An image of yourself "going all the way" and "seeing" that this happy abandon leads only to positive consequences may short-circuit our safeguards, allowing us to exert more force than normal. This is, however, at present only a speculation.

3. The longer one waits between mental practice and performance, the smaller the effect of mental practice. In fact, the benefit of mental practice drops to half its initial level after 2 weeks. After 3 weeks, the effects are so small that we could debate whether they are present at all. Is mental practice mimicking what happens in actual practice? Yes, it is. The benefits of actual practice also drop off with elapsed time, probably for the same reason: Memories typically degrade with time. However, once implicit memories become firmly entrenched, they do not decay much over time (Schacter, 1996); one supposedly never forgets how to ride a bicycle. Is the same true for mental-practice-induced implicit memories? One recent study suggests that the answer is "yes." In this study, participants either imagined typing or actually typed a set of key sequences and were tested 1 month later on these same key sequences and new key sequences. The mental practice group performed as well as the physical practice group for the practiced sequences, and both groups performed better on the practiced sequences than the new sequences (Wohldmann, Healy, & Bourne, 2007). These findings indicate that implicit memories generated through mental practice persist over time as much as implicit memories generated through physical practice.
4. In general, both novices and experts benefit from mental practice, but novices benefit more if the task involves heavily cognitive components (such as arranging moves into a sequence) than if it is more physical (e.g., focused on strength per se), whereas experts benefit to the same degree for both types of tasks. For novices, basic actions must be assembled into longer sequences, but experts have long since stored such sequences in memory (and probably have even made them automatic). For experts, mental practice may serve to remind them of which aspects of the situation need to be attended to and may alert them to junctures where they sometimes make mistakes (see Beilock & Lyons, Chapter 2, this volume).
5. The total optimal amount of time to devote to mental practice is about 20 minutes. More or less time reduces the benefit. Too little mental practice may not lead to the salubrious effects noted, and too much can lead one to incorporate errors into motor programs. That is, if one goes too long without actual feedback, one may come to be practicing the wrong moves and thus later will have to dig out of a hole, first unlearning these flawed behaviors. In addition, it is possible that too much mental practice is boring, and people thereby lose concentration (cf. Driskell et al., 1994).

THE IMITATING BRAIN

How can forming images result in implicit information being stored in memory (even if such information consists of modifying representations that were previously stored)? One key idea is that mental practice relies on creating *images you can imitate* (this notion extends the early "social learning" ideas of Carroll & Bandura, 1982). Let us start by thinking about normal imitation: Someone makes a series of gestures, and someone else mimics these movements. We rely on imitation so much, from learning to drive to learning to dance, that we take it for granted. If one could not watch someone else dance and imitate what they did, one would be forced to rely purely on explicit instruction and trial-and-error learning, which might be good enough to master the twist but is no way to learn the tango. Our point is that imitation is a key mechanism that underlies mental practice (whether or not mental practice is best in combination with physical practice or explicit instruction). The benefits of

imitative learning motivated the founder of modern Germany, Otto von Bismarck, to observe that fools learn from experience, but the wise person learns from the experience of others.

Imitation is in fact an amazing, almost miraculous, feat: Visual input (watching someone else) somehow gets converted to a "program" in the observer's brain, which then allows that person to make the same movements. How can observing someone else perform an act then allow you, with your different body and different point of view, to do the same?

THE NEURAL BASES OF IMITATION

Two recent discoveries can help us begin to understand how imitation works. First, researchers have found neurons in part of the frontal lobe that fire very selectively as an animal makes specific movements; some of these neurons fire as the animal grasps but not as it points or reaches, and others fire as it points but not as it grasps or reaches, and so on (Gentilucci et al., 1988; Perrett, Mistlin, Harries, & Chitty, 1990; Rizzolatti et al., 1988). These neurons represent a "vocabulary" of basic movements, and once triggered they lead the animal to produce a particular movement. Second, researchers have found that some of these basic-movement neurons respond even when the animal only observes another animal (or person) perform a specific behavior, even if the animal does not perform the action. These neurons have been dubbed *mirror neurons*. Again, each individual neuron responds only when a specific action is observed (e.g., Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; for review, see Rizzolatti & Craighero, 2004). And, we have good reason to believe that such neurons exist in the human brain; although responses of individual neurons have not been monitored in humans as they watch others behave, the results of neuroimaging studies have revealed activation in the appropriate parts of the frontal lobe when people watch someone else gesture (Decety et al., 1997; Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Grèzes, Armony, Rowe, & Passingham, 2003; Rizzolatti et al., 1996; for review, see Rizzolatti & Craighero, 2004). Given the similarities between the monkey and human brain, it is extremely likely that the human brain also is graced with mirror neurons.

We do not need a large leap of logic to suppose that mirror neurons play a key role in imitation. Mirror neurons do not simply register when one perceives specific actions; they also produce the corresponding behavior, and voila! we can do what we see. Why would the mirror neurons register perceived actions sometimes, but other times also produce those actions? The frontal lobes are known to contain many neurons with the job in life of inhibiting other neurons. Such inhibitory neurons can "turn off" performance when we do not want to imitate (probably most of the time). If the frontal lobes must actively intervene to stop us from imitating what we see, then it makes sense that young babies "automatically" imitate much of what they see (such as sticking out tongues); in fact, even 2-day-old infants can imitate facial expressions (Field, Woodson, Greenberg, & Cohen, 1982). The frontal lobes are the last lobes to become fully mature and do not inhibit behavior as effectively when we are very young, which we speculate might help to explain why "acting childish" is a synonym for acting impulsively, with little self-control.

IMITATING IMAGINED ACTIONS

Similarly, we do not need a large leap of logic to forge a connection between such neural machinery and the role of imagery in mental practice. Neuroimaging has shown that visual mental imagery activates about 90% of the same bits of the brain that are activated during the corresponding perceptual task (Ganis, Thompson, & Kosslyn, 2004). Moreover, there is much evidence that imagining something can later be mistaken for having seen it (for review, see Kosslyn, 1994). Thus, mental images can "stand in" for actual observation and—presumably—affect performance via the same neural mechanism that allows actual observation to affect performance: mirror neurons.⁵ Furthermore, with imagery you can "see" things normally impossible in real observation, most notably yourself performing an act. Psychophysiology research by Fourkas, Avenanti, Urgesi, and Aglioti (2006) suggests that imagining oneself from an external (i.e., third-person) perspec-

tive activates the same mirror neuron regions involved in the observation and execution of motor acts. Therefore, mental practice might work not only by allowing you to imitate imagined others but also by allowing you to imitate an imagined version of yourself. Moreover, we can speculate further that one can imitate the spatial and motor images, as well as visual feedback, experienced when one actually performs an action. In such images, one would "see" (and feel) things from a first-person perspective.

But, why do we need visual imagery at all to practice mentally? Why not just imagine the kinesthetic "feel" of flexing our muscles? We need visual imagery in mental practice for the same reason we need visual percepts during actual practice: We are practicing not only moving our bodies or limbs but also moving in relation to objects in the world. We need to relate our images to what we would see in the corresponding situation, and thus we cannot rely simply on kinesthetic images, but rather must use visual and spatial images as well.

Mental practice occurs when one imitates actions in an image but does not trigger the behaviors themselves (Berthoz, 1996; Jeannerod, 2001). Neuroimaging studies have shown that virtually all of the brain areas that plan and control actual motor acts also plan and control imagined motor acts, although to a lesser degree and in a task-specific (and probably strategy-specific) manner (Porro et al., 1996; Roth et al., 1996; for review, see Crammond, 1997; Decety & Stevens, Chapter 1, this volume; Jeannerod & Frak, 1999).⁶ Evidence suggests that the degree of overlap in functional neuroanatomy between imagined and performed acts increases with practice (i.e., as one learns a particular motor sequence), and that the changes in brain activation that occur as a result of actual practice correspond to those changes that occur as a result of mental practice (Lacourse, Orr, Cramer, & Cohen, 2005; Lafleur et al., 2002).

Although the vast majority of neuroimaging evidence is limited to the types of relatively simple motor tasks participants can perform in an functional magnetic resonance imaging (fMRI) or positron-emission tomographic (PET) scanner (e.g., foot tapping), a noteworthy exception comes from Ross, Tkach, Ruggieri, Lieber, and Lapresto (2003). In this study, golfers of different skill levels mentally rehearsed their golf swings while in a brain scanner. As expected, motor-related brain regions were activated when participants imagined teeing off. And, just like the studies of finger and toe tapping conducted earlier, the extent of this activation varied with skill: Golfers with higher handicaps actually used more of their brains during golf imagery than those with lower handicaps.

Researchers have also used transcranial magnetic stimulation (TMS) to show that the parts of the brain that control fine movements are activated by mental imagery. TMS is a relatively new technique by which a coil is placed on the skull at a location known to be over a specific part of the cerebral cortex. A large electrical current is run very briefly through the coil, which produces a strong, but very brief, magnetic pulse. This pulse in turn induces the neurons under the coil to fire (Pascual-Leone, Walsh, & Rothwell, 2000). Researchers have used this technique to stimulate the parts of cortex that control specific muscles; with the appropriate level of magnetic field strength, the TMS causes slight twitching of those muscles. Remarkably, if a person is imagining performing an activity that uses specific muscles, less TMS is required to get those particular muscles to twitch. The mental practice activates the appropriate brain area to a slight degree, which then requires less TMS to trigger the muscles (Fadiga, Craighero, & Olivier, 2005; see also Fadiga et al., 1999; Hashimoto & Rothwell, 1999).

Additional evidence that imagery engages brain systems used to control movements comes from studies of patients with Parkinson's disease. This disease depletes the amount of the neurotransmitter dopamine in parts of the brain that control movements and thereby disrupts the ability to move smoothly and well. Researchers asked patients with Parkinson's disease to reproduce a sequence of finger movements. As expected, these patients made the movements slowly. In addition, these researchers asked the patients not to move but instead to reproduce the movement sequence solely in their heads and report when they had finished. The patients imagined the sequence more slowly than normal, even though no actual movement was produced. This is as expected if the same neural

mechanisms are used to produce real movements and to mentally simulate them (Dominey, Decety, Broussolle, Chazot, & Jeannerod, 1995).

MENTAL PRACTICE: STEP BY STEP

Mental practice has different aspects, which are handled separately by different systems in our brains. Take something as seemingly simple as practicing a golf swing. How complicated could that be? Let us take a look, step-by-step.

We can divide mental practice into four phases: storing images, initial mental rehearsal, image correction, and advanced mental rehearsal.

PHASE I. STORING IMAGES

At the outset of learning a new skill (which may rely on rearranging sets of relatively simple movements that have been previously represented), one needs to store in memory a clear representation of what one would like to achieve. Fortunately, our brains store what we pay attention to, so to store an appropriate image one needs to observe what a master of the trade does. (We note, however, that it is possible that one's previous experience limits what one can notice and store, and that one must incrementally develop increasingly more refined images as one becomes more adept in the skill. But our point is that the image one does encode, within whatever limitations one has, serves a key role at the outset of learning a new skill.) One needs to observe carefully, however, because the quality of later imagery depends on the quality of initial information encoding. To profit from a good golf coach, one needs to observe very carefully how he or she stands and positions his or her shoulders, feet, and head and exactly how he or she moves at different phases of the swing. A good coach will help a student by explicitly pointing out each key feature and perhaps even exaggerating some of them so that the student will be sure to notice the critical information. The goal here is to store the appropriate information as deep representations in long-term memory (Kosslyn, 1980) as well as associations between sequences of such representations; these associations will allow one later to generate a series of images.

Here is a crucial point: We can store not only static images but also images of moving objects (including a person's limbs). This is important because one usually does not want to learn a new pose, such as holding a salute; rather, we want to learn a new way to act, which involves motion. In fact, researchers have found that recalling images of moving objects activates those parts of the brain that register movement during perception (Goebel, Khorrām-Sefat, Muckli, Hacker, & Singer, 1998; Grossman & Blake, 2001; see also Slotnick, Thompson, & Kosslyn, 2005). And, as predicted on the basis of the observation that imagery and perception share many of the same underlying brain mechanisms, imagining a moving object or pattern can alter perception. For example, have you ever stared at a waterfall for a few minutes and then turned your gaze to a stationary object? If so, you have probably noticed an illusion: The stationary object will seem to be moving upward, in the opposite direction as the waterfall. A very similar illusion can be induced simply by visualizing a moving pattern and then viewing a stationary one, which is good evidence that imagining movement engages brain mechanisms used in perceiving movement (for review, see Kosslyn, Thompson, & Ganis, 2006).

PHASE II. INITIAL MENTAL REHEARSAL

If one has stored the appropriate information in implicit memory and can generate the corresponding mental images and then inspect them, is this enough to learn that swing? After all, we have claimed that one can imitate images. There are two problems with this simple idea: The first is that one does not actually study oneself. The coach has a different body than the student's, and thus the student needs to transform the image ("fine-tuning" it) so that the movements fit his or hers. The second is

that one may have moved one's eyes while studying the coach, fixing attention on one part of his or her movements at a time—and hence stored a series of separate images. So, one needs to integrate what has been stored piecemeal into a single, flowing action. To learn a single motion, such as arching the back, a single dose of mental practice may be enough. But to learn complex motions (such as a golf swing) and to assemble a set of motions into a single sequence, repeated episodes of mental practice are required. Each specific movement needs to be imitated correctly, in the right sequence, with just the right timing and amount of force. If one has a good image of the coach, it is possible to notice when one is not doing the mental practice properly and to correct the mental actions.

PHASE III. IMAGE CORRECTION (RE: THE BEST LAID PLANS OF MICE AND MEN)

Mental practice is only as good as the images used. Thus, perhaps paradoxically, an important part of mental practice is real practice. Particularly at the outset, feedback is necessary; one needs to see what actually happens when the mentally practiced motor programs (i.e., sequences of commands that control movements) are implemented in real life.⁷ Thus, prior to actually performing the move, one should visualize oneself doing it—and then compare what actually happens when the act is performed to what was expected to happen on the basis of the mental simulation.

However, to take full advantage of feedback, some researchers have argued that in most activities one first must have shifted the image from an *external perspective* (seeing oneself as if from another person's point of view, from the "outside") to an *internal perspective* (seeing the situation as one would when actually performing the action, from the "inside"; Hale, 1994; see also Libby & Eibach, Chapter 24, this volume). In interviewing gymnasts who had qualified for the Olympics, researchers found that most of them reported using internal imagery to mentally practice; in sharp contrast, an otherwise similar group of gymnasts who had not qualified for the Olympics reported mostly using external imagery (Smith, 1987).

Why should the image perspective matter? After one generates images from an internal perspective, one can easily compare what happens when actually performing the action with what was expected to happen based on imagery. Indeed, when people were asked to take the two perspectives while their brains were scanned as they imagined making actions, researchers found that taking the internal perspective activated the part of the brain that most sensitively registers tactile sensations, the *somatosensory cortex*, more than did taking an external perspective. This cortex may allow us to "feel what would happen" when we move, which is crucial for comparing an imagined action to an actual action (Ruby & Decety, 2001; other brain areas were also activated differently when people adopted one or the other perspective, which clearly demonstrates that different processes underlie taking each of the two perspectives). And, based on such matching, one can tune imagery appropriately, changing it to improve both the image itself and the corresponding actions.

PHASE IV. ADVANCED MENTAL REHEARSAL

Advanced mental practice has the goal of making a complex performance automatic, of not only storing a set of new motor movements as implicit memories but also associating each movement with cues that will immediately trigger it in the proper setting. Part of this process involves making the sequence of small actions so cohesive that the entire sequence becomes a single unit. We do not want to be lost in thought before we hit each ball. The distinction between "conscious and effortful" versus "unconscious and automatic" is directly reflected by the existence of two separate brain systems for learning. One system relies on consciously using mental representations, and the other system relies on responding unconsciously to stimuli. The first sort of learning has been dubbed *cognitive learning*, whereas the second has been called *habit learning* (Mishkin & Appenzeller, 1987). As a first pass (which is undoubtedly an oversimplification), the cerebral cortex is crucial for the first sort of learning, whereas the basal ganglia (structures deep within the brain) and cerebellum ("little brain") come to the fore when implicit information about movements is learned. These

latter structures hook stimuli relatively directly to responses, allowing one to shift from first gear to second as soon as the engine is revving fast enough, to smile when meeting someone, and to lock the door when leaving home. One hallmark of such automatic behaviors is that we usually are not aware that we have done them, even immediately afterward.

However, most of the time one needs to adjust what one does to the specific circumstances at hand. For a golf swing, one needs to adjust how hard to hit the ball to fit the distance it needs to travel, and of course one needs to aim properly (which will require integrating various sorts of information, including factors such as the direction and force of the wind). Thus, the implicit information one stores via imagery may in fact need to be retrieved, at least in part, via imagery and integrated with current circumstances.

CONCLUSIONS

Mental imagery and implicit memory affect each other and together affect behavior. On one hand, implicit memories often affect imagery, and in this sense, imagery is a mental application of implicit memory. On the other hand, implicit memories can be affected by imagery; in this sense, imagery plays a role in forming implicit memories. In this chapter, we focused on mental practice as a prime example of the relationship between imagery and implicit memory. In mental practice, implicit memory and imagery processes interact: The accurate generation, maintenance, manipulation, and integration of imagery during mental practice hone the implicit, procedural memories that help to give rise to this imagery in the first place, and honed implicit memory in turn alters imagery. This interaction culminates in improved physical performance, examples of which have been documented across a striking range of activities.

The circumstances in which mental practice is effective, or is most effective, make sense in light of this interaction between imagery and implicit memory. For example, mental practice has larger effects for more cognitively complex activities, as one would expect if mental practice operates by refining implicit memories. Recommendations for mental practice also flow logically from this perspective. Procedures that improve the quality of relevant implicit memories and mental images will increase the positive effects of mental practice. For example, careful observation of skilled behavior will lead to better implicit memory, better imagery, and therefore more effective mental practice.

Imitation, we argue, is a key mechanism of mental practice because it bridges observation and action. Just as we can imitate perceived others, we also can imitate imagined others—or imitate images of ourselves performing an action. The imagined models that we imitate rely on information stored implicitly, and our imitations—be they of real or imagined models—feed back to affect our implicitly stored information.

Finally, although mental practice is the most researched instance of how imagery and implicit memory interact to affect behavior, other possible examples exist. In particular, research suggests that mental imagery can be used to alter implicit stereotypes (Blair, Ma, & Lenton, 2001) and attitudes (Akalis, Nannapaneni, & Banaji, 2006). As psychologists continue to explore the intersection between imagery and implicit memory, we expect many additional examples of theoretical and practical significance to emerge from these efforts.

ACKNOWLEDGMENTS

Preparation of this chapter was supported by National Science Foundation grant REC-0411725 and National Institutes of Health grant 2 R01 MH060734-05A1.

NOTES

1. This claim is consistent with Pylyshyn's (1981, 2003) notions about "tacit knowledge," but we are claiming that such knowledge guides imagery—as opposed to being a substitute for it. For a detailed discussion of the relevant issues, see Kosslyn et al. (2006).

2. For an amazing video of high-voltage cable inspection, see http://www.youtube.com/results?search_query=High+Voltage+Cable+Inspection.
3. One of the most revealing details of Yue and Cole's (1992) study is that significant strength gains (20%) were also found in the contralateral, untrained finger. This finding strongly suggests that mental training affected the psychomotor processes that control finger movement rather than the peripheral nervous system or muscular activity that implement such commands.
4. This idea is based on one originally proposed by Nick Humphreys (personal communication, September 2000) to account for placebo effects; he bears no responsibility either for our misunderstanding his theory or for our application of it.
5. For evidence that the mere observation of an act can affect the subsequent performance of that act, see Brass, Bekkering, Wohlschläger, and Prinz, 2000; Brass, Bekkering, and Prinz, 2001; Brass, Zysset, and Cramon, 2001; Castiello, Lusher, Mari, Edwards, and Humphreys, 2002; Edwards, Humphreys, and Castiello, 2003.
6. The motor imagery literature in many ways parallels the visual imagery literature. At first, researchers claimed that the primary motor area (which controls fine movements) was not activated, only the higher-level areas that program movements. Later studies revealed that even the primary motor area is indeed activated during motor imagery (e.g., Roth et al., 1996; Schnitzler, Salenius, Salmelin, Jousmaki, & Hari, 1997; compare the review in Jeannerod, 2001, with that in Jeannerod & Decety, 1995). Indeed, Erslund et al. (1996) went so far as to ask a man who had his right arm amputated to imagine moving the fingers of his right hand; fMRI revealed that the primary motor cortex that would have controlled those fingers was active during this task, even though his hand was no longer present.
7. In fact, when mental practice is occasionally supplemented with actual practice, some researchers report that participants improve as much—or even more—than with only physical practice (e.g., see Richardson, 1967; Weinberg, 1982). However, this pattern does not always hold up (e.g., Meyers, Schleser, Cooke, & Cuivillier, 1979). Clearly, the effects of mental practice not only vary for different sports (as we would expect, given their different requirements) but also depend on exactly what is done (cf. Feltz & Landers, 1983).

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