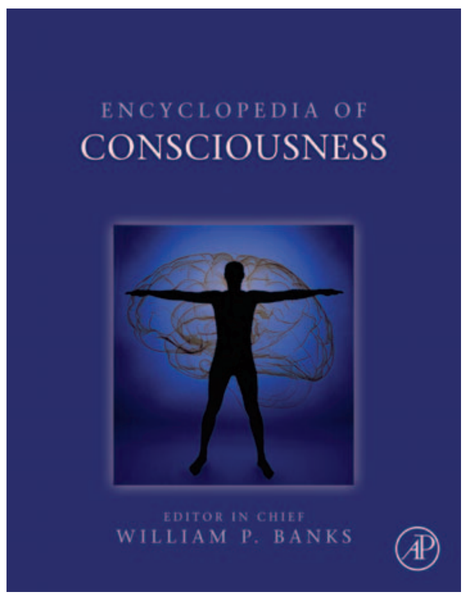

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Memory: Procedural Memory, Skill, Perceptual-Motor Learning, and Awareness

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Glossary

Closed-loop process – Process that uses information about its outcomes as input.
Declarative memory – Memory for knowledge about facts.
Episodic memory – Autobiographical memory, part of declarative memory.
Open-loop process – Process that does not use information about its outcomes as input.
Perceptual-motor learning – Learning of motor skills that rely on perceptual input.
Procedural memory – Memory for knowledge about how actions are executed.
Schema – General knowledge structure in memory about a particular type of action.
Semantic memory – Memory for meaning, part of declarative memory.
Skill – Overlearned behavioral routine resulting from practice.

Introduction

Anybody who has ever learned to ride a bicycle, or play the piano, will admit that mastering such skills requires lots of practice. And when asked how we acquire those skills, that is about all we have to say about it. We may be able to describe the principles by which a bike functions, or the structure of chords, but unlike such declarative knowledge, the knowledge about how our actions are executed – that is, procedural knowledge – that we acquire during skill development is not open to introspection. This seems even more remarkable if one considers the challenges that are faced in such learning processes. We never make the exact same bike ride twice, or play the same arpeggio on the piano, yet somehow we are able to extract general knowledge about the motor actions involved, store it in memory, learn to plan and tune those actions based on perceived feedback, and learn how they can be combined into complex sequences of actions without much awareness of what is going on.

Perceptual-Motor Learning

The problems with storing an action in memory already become apparent if we look at the simple act of, say, grasping a coffee mug. In any instance, we have never executed the exact required action before (the location of the mug and its handle are different) and even more problematic, we can execute the action in an infinite number of ways. One can flex and extend the different joints that are orchestrated by many different muscles in an infinite number of ways with the same result. We are, for example, still able to grasp the mug when holding a phone between our ear and the shoulder of the grasping arm and get the job done in an awkward, but effective, way. This degrees-of-freedom problem suggests that knowledge about actions cannot be stored in terms of exact knowledge of muscle tension and joint positions, but has to be represented in a more general way.

It turns out that what is stored in memory is the general pattern or schema that captures the essential structure of the action, with specific parameters to be filled in during the planning and execution of the action. This requires integration of knowledge from memory and information resulting from perception. The crucial role of visual feedback in the execution of actions has, for example, been demonstrated in studies in which perception was blocked by turning off the lights once participants had planned and started to execute the movement. Except for extremely quick, reflex-like actions – which are more ballistic in nature – performance significantly deteriorated without visual feedback. This demonstrates that even performance of a simple action is

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not an open-loop process, in which the action is only planned and then blindly executed, but a closed-loop process that requires integration of perceptual as well as motor information.

When it comes to executing skilled behaviors, it is especially this tuning of action, based on closed-loop processes, that we are mostly unaware of. We may consciously initiate a turn with our bike, but the processes by which we maintain our balance and stabilize our course in the new direction operate largely outside of awareness. This lack of consciously accessible knowledge about tuning becomes apparent in the following phenomenon. When you ask participants in the laboratory to demonstrate the steering movements that they usually make to change lanes with their car, most people turn the wheel in the required direction, and then turn it back to the starting position. In reality, it takes an equal turn in the opposite direction after changing the lane to keep the car on the road. Apparently, although people are consciously aware of the movement they must make to initiate action, they lack conscious knowledge of the subsequent compensating movement that relies on tuning in response to visual feedback.

Sequence Learning

In addition to this lack of conscious knowledge of tuning, people are often oblivious to how sequences of actions are learned. Researchers have since long been intrigued by the question of how rapid sequences of actions in playing piano, or typing, can be learned and executed, especially because there is no time to receive the feedback of one action before performing the next. Although it was first believed that such sequences were stored in memory as action chains, in which each specific action that was retrieved from memory would trigger retrieval and execution of the next associated action, by now it has become clear that people do not so much store the chain of the exact responses, but rather a more abstract, higher-level pattern. This was revealed by studies showing that execution of a specific action-pattern benefited from an earlier learning phase, even when the exact actions during that learning phase (pressing a series of buttons with one's hand) were executed by a different means in the test phase (e.g., pressing the same series of buttons with one's elbow).

Learning of such action sequences is one of the pillars of skill development and has been shown to occur even without conscious awareness. In classic studies on implicit sequence learning, participants responded with different actions to different stimuli that occurred in a fixed, but rather complex pattern. Even though participants did not consciously detect any pattern, they speeded up over time and performance significantly deteriorated when the stimuli were no longer presented according to the fixed pattern.

Organization of Skills in Memory

But even when such sequences are learned there is room for improvement in execution. One of the characteristics of skills is that they keep improving, although ever less dramatically, over time. An important mechanism that contributes to this effect may be more efficient storage of action patterns in memory. Typing lessons capitalize on this knowledge by having people repeat often occurring patterns of keys (e.g., 'T-H-E') over and over again. Although it is clear to the student what has to be learned, the pattern of movements has to be 'stamped in' through practice. This strategy promotes the grouping of specific actions in memory into chunks, which also happens over time without specific practice. These chunks can then be retrieved from memory and executed as one unit.

Brain Processes, Skill-Learning, and Awareness

Studying skill acquisition in people with specific brain lesions, as well as modern neuroimaging methods such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have made it possible to gain knowledge about the areas of the brain that are involved during several stages of skill development. One striking finding is that brain structures that are crucial in memory for events have little to do with skill acquisition. Studies with patients suffering from anterograde amnesia have demonstrated that although those patients are unable to form new memories about events, they develop many skills just as well as control participants. It has been demonstrated that this skill-learning goes even further than perceptual-motor skills. In one study, amnesic and control participants practiced reading of words that were presented in mirror image in a series of learning blocks that extended over a 2-week period. Some specific words were repeated from block to block, whereas the rest of the words were always novel in each block. Although the reading time per word for the repeated words dropped faster for control participants than amnesiacs, mirror-reading skills for novel words were shown to improve equally fast for both groups. Hence, although control participants clearly benefited from the memory of having seen the specific repeated words (which they could consciously recall) in previous blocks, amnesiacs developed the same mirror-reading skill without any recollection of those words.

These findings demonstrate that procedural and declarative memories are supported by distinct brain areas. In declarative memory, the hippocampus has been found to play a crucial role. Bilateral damage to the hippocampus and parahippocampal regions indeed causes retrograde amnesia, with loss of episodic memory and semantic memory. These structures also play a crucial role in certain types of learning, such as trace conditioning, where there is a relatively long time lag between a neutral conditioned stimulus (CS) (e.g., a tone) that predicts an unconditioned stimulus (US) (e.g., a puff of air in the eye). Although after conditioning in such a task animals with an intact hippocampus react with an eye blink to the CS, such learning does not occur when the hippocampus is damaged. The same effect has been demonstrated in humans, where this type of learning is accompanied by activation of the hippocampus and usually with conscious awareness of the relation between the CS and the US. In sum, the hippocampus plays a crucial role in declarative memory, but also in particular forms of learning, where integration of separate events in memory is required.

The brain areas involved in procedural learning, and in particular the learning of motor skills, change as learning of the skill progresses. In the early stage of motor-skill learning, the prefrontal cortex (PFC), anterior cingulated cortex (ACC), and posterior parietal cortex (PPC) direct attentional and control processes that are necessary for grasping the basics of the task and the planning of deliberate, intentional responses. As skills start to form, the cerebellum plays a crucial role in creating ‘mental shortcuts’ between perception and actions. It integrates afferent signals coming in from the sensory systems with efferent signals that produce motor actions. As such, it links together new and already acquired motor-programs, forming more complex response patterns and assigning them to particular perceptual patterns. Activation of the cerebellum is typically found in the early stages of skill-learning and shifts from the cerebellar cortex to the nuclei as learning advances, until it almost ceases when a basic skill is acquired.

In this stage, the striatum has been found to play an important role in the detection of errors that are produced. When erroneous responses occur, the inappropriate programs are inhibited, a process in which the PFC is again thought to play an important role. As a result, connections between perceptual input and the appropriate motor output are further strengthened. Thus, the skill is further polished until it is executed almost flawlessly.

If this skill is then used frequently over a longer period, the skill becomes overlearned, which will finally lead to changes in the motor areas that play a role in the execution of the specific motor actions. Such cortical plasticity has been demonstrated in, among others, musicians and professional sportsmen, in whom the mapping of crucial motor programs has been reorganized in service of their skills. As such, overlearned skills become more and more hardwired in people's brains, and conscious attention or awareness are no longer required to conduct them.

Acquired Skills, Goals, and Conscious Control

Although the execution of a skill may eventually occur without conscious awareness, skills are often executed in the service of a conscious goal. Grasping a mug and bringing it to one's mouth, for instance, usually serves to take a sip of the fluid contained by the mug (e.g., coffee). Because acquired skills are stored as abstract high-level patterns, skill execution such as grasping the mug can be elicited by merely perceiving a skill-relevant cue (e.g., a coffee mug) under many different circumstances (e.g., under variations in distance toward the mug, or size of the mug) once a goal is set. As a result of overlearning, little or no conscious control is needed to execute the individual action sequences that capture the essential structure of the action (e.g., when and how much a hand should be opened when reaching for the mug). In fact, it has been shown that focusing conscious attention on the execution of specific components of a complex motor skill can impair performance.

For instance, experienced golfers are better in putting a ball when they are distracted by a secondary task (e.g., monitoring whether a specific tone sounds through a headphone) than when they are instructed to focus attention on their swing. In a similar vein, experienced soccer players, but not novices, handle the ball better with their dominant foot when they are distracted from executing a skill (e.g., dribbling) than when they consciously focus on specific components of the actions that they are executing. An explanation for this effect is that by attending to separate components one overrules the more efficient organizational structure of the skill, causing the building blocks of the skill to function as separate components, in pretty much the same way as before the skill was acquired. Once the organizational structure breaks down, each component is executed separately, which costs more time, and leaves more room for error, than when the abstract high-level pattern is used to execute the separate components. It has been proposed that conscious attention to the step-by-step components of motor skills can lead to choking under pressure, for instance when a soccer player misses a penalty kick. Conscious control can, however, be beneficial if skills are not yet overlearned. It can, for example, improve performance in experienced soccer players when they handle the ball with their nondominant foot, or in novices in general, indicating that conscious attention toward action components can be helpful in practicing, or tuning, an underdeveloped skill.

Although conscious control can be detrimental to performance of complex goal-directed skills, conscious control may be experienced over the overall action if one reflects on one's behaviors, as long as the outcome of the action (e.g., the golf ball rolls in the hole) is congruent with the goal that started the execution of the skill (e.g., putting the ball in the hole). Thus, even though awareness – and conscious control – of specific components of overlearned skills can be very restricted, conscious control can nevertheless be experienced when an intended outcome is reached. It appears that what is needed for an experience of control is that the outcome of an action is congruent with the mental representation of an intended outcome, irrespective of whether one actually consciously controls each and every step of the action sequence.

The lack of conscious control over our skills, however, becomes apparent if our skills produce other outcomes than we consciously intended. As noted above, skill execution can be easily elicited by perceiving a skill-relevant cue when one has a goal in mind. If you want to use your computer, for instance, perceiving the log-in screen may trigger the responses required to log-in (e.g., typing in the correct password) without much conscious deliberation, if this procedure has been performed a great number of times before. Although this efficiency has a great advantage, as it relieves consciousness from tedious tasks such as retrieving a password from declarative memory, it also comes with a cost: It can be hard to prevent skill execution when a goal requires a new response that is different from an overlearned behavioral routine. For instance, when the password of your computer is changed, it is possible that the old password is entered erroneously the first couple of times that you start the computer. This example illustrates that an overlearned behavior (typing in the old password), which is no longer instrumental in attaining the goal (starting your computer), is still easily triggered by the environment. When there is a discrepancy between the outcomes produced by our skills and our intended outcome (starting the computer), we become aware of the situation, and conscious control can be recruited to choose a new path of action in order to reach the intended outcome (e.g., consciously retrieving the new password from declarative memory). Of course, with repeated practice, conscious control will again become less necessary and perceiving the log-in screen will be sufficient to trigger the adjusted skill.

Conclusion

From perceptual-motor to sequence learning, procedural knowledge is acquired as skills develop, although most of the time this knowledge is not accessible to consciousness. Acquiring a skill takes a lot of practice, during which different brain processes are involved in creating stable mental maps of the skill. Although it may seem to be a disadvantage in that there is no other way of acquiring this knowledge than through practice, the major benefit of procedural memory over declarative memory (which relies on different brain areas) is that it is highly stable. Once one has learned to ride a bike one never forgets. Although sometimes these skills may produce different outcomes than consciously intended, on the whole they serve us well, by freeing up precious capacity for other conscious processes. This process is so effective that conscious attention to skills may even deteriorate performance. Thus, skills make it possible to behave very effectively without much conscious interventions. In this light, the lack of introspection in how we acquire them may be a small price to pay.

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See also: Habit, Action, and Consciousness; Perception, Action, and Consciousness.

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Biographical Sketch

Ruud Custers received an education in human–technology interaction at Eindhoven University of Technology, where he graduated cum laude on work investigating the role of memory in the formation of judgments about environments. Subsequently, he moved to Utrecht University to pursue his PhD in experimental social psychology. He received his PhD cum laude in 2006 for his dissertation on the underlying mechanisms on nonconscious goal pursuit, which mainly focused on the role of affective signals in this process. He published several papers in fundamental journals, of which one was regarded as the best paper of the year on social cognition by the International Social Cognition Network in 2006. As an assistant professor at Utrecht University, he continues to study the processes that allow people to pursue goals without conscious awareness.

Harm Veling is trained as an experimental social psychologist at Radboud University Nijmegen where he worked on intention memory and inhibitory control. He received his PhD in 2007 for his dissertation on the inhibitory processes that facilitate execution of previously formed intentions. Next, he continued to work as a postdoc at Utrecht University. His work deals with several topics related to the role of goals and actions in automatic processes of social cognition, with an emphasis on inhibitory processes, and is published in several fundamental journals. One recent discovery in his research concerns the notion that stopping an action that is initially triggered by a rewarding stimulus results in devaluation of the rewarding stimulus. This chain of events suggests a functional behavior regulatory dynamic. He continues to study this intriguing and important topic.