14 From novice to expert performance

Memory, attention and the control of complex sensori-motor skills

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From the naissance of systematic skill acquisition research in the late 1800s (see Bryan and Harter, 1899) to the present day, investigators of human skill have explored differences in expert and novice task execution in an attempt to shed light on the variables mediating high-level performance. These investigations have not only been concerned with the measured success of overt performance at various levels of task experience, but also with changes in the cognitive mechanisms, such as memory and attention, that underlie performance improvements as learning progresses (Allard and Starkes, 1991; Anderson, 1982, 1983; Beilock and Carr, 2001; Ericsson *et al.*, 1993; Fitts and Posner, 1967; Reimann and Chi, 1989).

What makes expert performance different from novice execution? At first glance, one might suggest that the answer is simple. It is the quality of overt behaviour that separates exceptional performers from those less skilled. We can all point to many 'real-world' examples of such performance differences; just try comparing any professional athlete to his or her recreational counterpart. Although actual performance is one component that differentiates experts from novices, researchers who approach skill acquisition from a cognitive perspective believe that these overt performance distinctions are only part of the picture. Indeed, they are viewed as merely the surface manifestation of skill level differences. The cognitive control structures that support planning and drive execution are what is thought to truly distinguish novice from expert performance. These control structures rely on particular forms of memory and vary in the demands they place on attention. Both the memorial substrate and attentional demands of these control structures change as practice accumulates and skill proficiency increases.

Theories of skill acquisition

Cognitive theories of skill acquisition and automaticity suggest that performance proceeds through identifiably different phases as learning progresses, characterized by both qualitative changes in the cognitive substrate governing execution and in performance itself. A number of different frameworks have been proposed to capture these skill level differences. Fitts and Posner's (1967) three-stage model of skill acquisition suggests that early in learning, novices use explicit

cognitive processes to control execution in a step-by-step fashion. Because of the involvement of conscious cognitive processes early in learning, Fitts and Posner termed this initial stage of skill learning the *cognitive phase*. Once learners understand the nature of the task, they are thought to enter an *associative phase* in which the need to consciously control real-time performance diminishes, and task representations are established that directly connect stimulus situations to actions. With extended practice, performance reaches the *autonomous phase*. In this final stage of learning, skill execution is based on a fully automatic task representation in which conscious attentional control is no longer required to execute a particular action when confronted by a particular stimulus situation.

While Fitts and Posner's (1967) characterization of skill level differences has been extremely influential to the study of human skill acquisition, their framework is mostly descriptive in nature. In an attempt to assign specific knowledge structures to Fitts and Posner's stages of learning, Anderson (1982, 1983, 1993) has developed a formal simulation model of skill acquisition most recently known as ACT-R (Anderson and Lebiere, 1998). In this model, skill learning is thought to progress from a *declarative phase* (similar to Fitts and Posner's cognitive phase) to a *procedural phase* (corresponding to Fitts and Posner's autonomous phase), through a process known as *knowledge compilation*. In ACT-R's early declarative phase, performance is thought to be based on declarative knowledge (i.e. facts and information about skill execution) that must be held in working memory during online execution. Working memory can be thought of as a short-term memory system that maintains, in an active state, a limited amount of information with immediate relevance to the task at hand (Proctor and Dutta, 1995). This information is used small amounts at a time by limited-capacity control processes, which guide performance in a step-by-step fashion. As learning progresses, declarative knowledge is said to be converted or compiled (through the process of knowledge compilation) into procedural knowledge that captures the instructions for performing the task at hand in a new form. Procedural knowledge is made up of 'productions' which represent knowledge about how we do things, for example, knowledge about how to kick a soccer ball. Unlike declarative knowledge, procedural knowledge does not require the active maintenance of each step of task execution in working memory. This more implicit type of knowledge is thought to run-off from one production to the next without explicit attentional control. When experienced soccer players kick a ball, for example, they do not think consciously about every component involved in kicking, they 'just do it' – supported by an automatic procedural control structure.

Thus, in general, cognitive theories of skill acquisition and automaticity suggest that novel skill performance is based on explicitly retrievable declarative knowledge that is held in working memory and consciously attended in real time (Anderson, 1983, 1993; Fitts and Posner, 1967; Proctor and Dutta, 1995). As learning progresses, information is restructured into a new type of skill representation, usually called a 'procedure' in the domain of cognitive skills, but often called a 'motor program' in the domain of sensori-motor skills (Brown and Carr, 1989; Keele, 1986; Keele and Summers, 1976). This new skill representation

does not mandate the same degree of attention and control that was necessary at lower levels of practice, and is supported by different neural structures than were active early in learning (Raichle *et al.*, 1994).

In this chapter, we explore some of the implications of these differences in the representation and operation of the control structures supporting performance at various levels of skill learning and expertise. Specifically, we examine how the memory structures and attentional demands associated with task execution differ as a function of skill level. Such an investigation will not only make salient those variables distinguishing novice and experienced performance processes, but may also aid in the development of strategies for enhancing the acquisition and maintenance of high level skills across a variety of attention-demanding and pressure-packed situations. We focus on sensori-motor skills of the type required by sports performance, and we believe that theories like those of Fitts or Anderson describe such sensori-motor skills fairly well. At the end of the chapter, we will briefly consider how widely these theories of 'automatization via proceduralization' might generalize to other domains of skilled performance.

Memory and skill acquisition

One of the most widely discussed characteristics of expert performance is the ability of highly skilled individuals to recall task-relevant stimuli within their domain of interest (Proctor and Dutta, 1995). In their classic chess studies, Chase and Simon (1973) found that chess masters were better able to recall briefly presented structured chess positions than were less experienced players (for confirmatory data, see De Groot, 1978). Similarly, expert computer programmers have been shown to have greater memory for realistic programming code sequences than less experienced individuals (McKeithen *et al.*, 1981). In sensori-motor skills such as dance, Starkes *et al.* (1987) have demonstrated that when expert and novice ballet dancers are presented with a series of choreographed movement sequences and asked to recall these movements either verbally or physically, expert dancers are better able to do so than their novice counterparts.

Why do experts show this superior memory ability in comparison to their less skilled counterparts for structured stimuli within their domain? Ericsson and Polson (1988) have developed a theory of skilled memory in an attempt to answer this question. Skilled memory theory suggests that experts encode stimuli in a style that allows them to store this information as associations of patterns in long-term memory. In essence, experts have learned to organize knowledge in their domain in a manner that allows them to easily take in new information about the stimuli they act on and subsequently retrieve it (for a review of skilled memory theory, see Ericsson and Polson, 1988; Staszewski, 1988).

But do experts have superior memory for all aspects of performance? Highly skilled performers may have better episodic recollection for the stimuli in the environment that they operate on (e.g. chess game configurations, basketball play scenarios or choreographed dance sequences). They may also have better

memories for the outcomes or results that their operations produced. That is, the new stimulus configurations that were created by their activities and whether these results achieved the desired goals (did the knight end up in the right space to hem in the queen or did the jump shot go in the basket?). But what about the mental events that led to these outcomes or the details of the actions the mental events controlled? It has not been demonstrated that experts have better memories than novices for all aspects of execution. In particular, this applies to the sequences of thought processes and executed actions that were responsible for changing the initial stimulus situation into the outcome situation. Indeed, from the theories of skill acquisition and automaticity presented in the previous section, it could be concluded that experts should actually have *worse* memories for these aspects of performance in comparison to less skilled individuals.

The theories of skill acquisition we have reviewed suggest that highly practised or overlearned performances are automated, supported by procedural knowledge that operates without the need for explicit or attended monitoring (Anderson, 1983, 1993; Fitts and Posner, 1967). It has been demonstrated that the successful explicit retrieval of information from memory is dependent on attention to this material at the time of encoding (Craik et al., 1996; Naveh-Benjamin et al., 1998). Thus, if experts are not explicitly attending to online performance, their memories for the step-by-step components involved in achieving a performance outcome as it actually unfolds in real time may be impoverished. Diminished memories of how a performance was actually achieved may make it difficult for experts to reflect and introspect on past performance decisions, strategy choices and execution processes implemented during task execution (Abernethy et al., 1993). This information is not only needed to learn and improve from past performances, but also utilized in the dissemination of knowledge to others when high-level performers assume the roles of teachers or coaches. Thus, the very cognitive changes that accompany becoming an expert performer could make it more difficult to teach one's skill to another person.

In an attempt to examine the memory structures supporting performance at different levels of learning, Beilock and Carr (2001) assessed the generic knowledge and episodic memories of expert and novice golfers. 'Generic' knowledge captures prescriptive information about how a skill is typically carried out. 'Episodic' knowledge on the other hand, captures an autobiographical record of a particular performance, a memory for a specific instance of skill execution. Experienced golfers may well give longer, more detailed generic descriptions of the steps involved in a typical or 'generic' putt compared to the accounts given by novices because experts know more about how their skill should be performed and can call this declarative knowledge to mind when reflecting 'offline'. However, if the real-time performance of well-learned golf putting is supported by procedural knowledge, as theories of automaticity and skill acquisition would predict, then experienced golfers may give shorter, less detailed episodic recollections of any particular putt in comparison to less skilled golfers. Proceduralization reduces the need to attend to the specific processes by which

skill execution unfolds, and reduced attention to performance decreases the likelihood of an explicitly accessible episodic performance memory.

Experienced golfers with more than 2 years of high-school varsity golf experience or a Professional Golfers' Association (PGA) handicap less than eight and novice golfers with no previous experience of the game served as participants. Individuals performed a golf putting task on a carpeted indoor putting green ($3\,\text{m} \times 3.7\,\text{m}$). They were instructed to putt a golf ball as accurately as possible, making it stop at a target marked by a square of red tape. All participants alternately putted from nine different spots, located at varying angles and distances from the target. Participants took part in a pre-test condition consisting of twenty putts, a practice condition consisting of thirty putts, and two post-test conditions. The first post-test consisted of twenty putts while the second post-test consisted of ten additional putts. Putting accuracy was recorded after every putt and an average accuracy score was computed for each condition (for details, see Beilock and Carr, 2001). Following the pre-test and practice conditions, participants produced generic knowledge protocols – what one ought to do on a typical putt. Individuals were instructed: 'Certain steps are involved in executing a golf putt. Please list as many steps that you can think of, in the right order, which are involved in a typical golf putt.' Following both the first and second post-test conditions, participants were asked to describe, in as much detail as possible, their episodic memories of the last putt – their memory of what they actually did on that specific putt. In order to obtain episodic performance memories participants were instructed: 'Pretend that your friend just walked into the room. Describe the last putt you took, in enough detail so that your friend could duplicate that last putt you just took in detail, doing it just like you did' (for detailed protocol instructions, see Beilock and Carr, 2001; Beilock *et al.*, 2002c). The first episodic memory protocol was a surprise. The second was expected. Prior to the last putt taken before the second episodic memory protocol, participants were warned to keep track of their putting performance, as they would be asked to produce an episodic memory of the next putt.

Memory protocols were first analysed in terms of the number of steps given in each protocol. Three expert golfers and a 'how to' golf putting book (Jones *et al.*, 1998) were employed to establish a master list of steps involved in a successful golf putt that could be used as a guide in coding the protocols. The statements in each participant's protocol were compared with this master list. If a step given by a participant referred to the same action or the same biomechanical principle as a step on the master list, it was counted as one step.

As can be seen in Figure 14.1, novice golfers gave short generic descriptions and longer episodic recollections. Experts produced an opposite pattern. Experienced golfers gave longer and more detailed generic descriptions than novices, yet shorter episodic recollections in comparison to both their generic descriptions and the episodic recollections of novices. Experts' impoverished episodic memories for online execution demonstrate what Beilock and Carr (2001) called 'expertise-induced amnesia'. Highly skilled online performances are controlled by automated procedural knowledge that operates largely outside
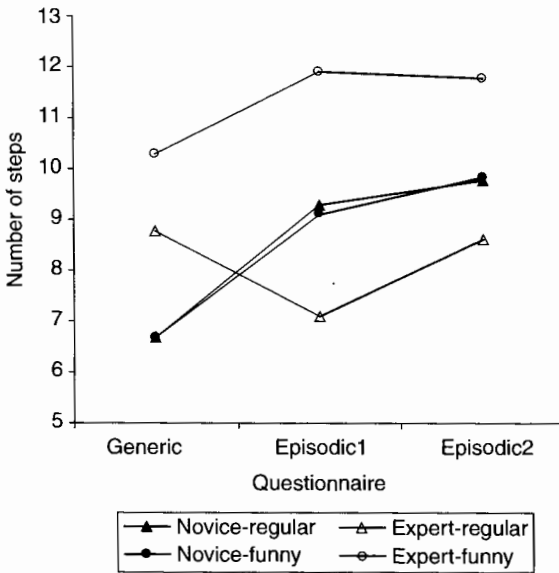
Figure 14.1 Mean number of steps for the generic questionnaire and the two episodic
         questionnaires for the novice and experienced golfers using the regular
         putter and the funny putter. Adapted from Beilock and Carr (2001).

the scope of attention and, therefore, is substantially closed to explicit analysis
and report. As a result, memories for the step-by-step processes involved in
performance are diminished in comparison to less skilled individuals.

The second episodic memory test, in which participants knew in advance that
they would be required to recall an episodic memory of their last putt, generated
the same results. Experts gave diminished episodic recollections in comparison
to novices. Thus, it is not just that experts choose not to pay attention to skill
execution in a manner that allows them to explicitly remember their perform-
ance. It is as if experts *cannot* pay enough attention to remember as well as
novices, at least when performing under heavily practised conditions.

Is it *always* the case that experts do not explicitly attend to step-by-step
performance and, as a result, memories for skill execution are impoverished?
If experienced individuals were never able to pay attention to real-time execu-
tion, one might imagine that they would have trouble correcting performance
flaws or altering skill execution parameters (e.g. revamping a golf swing or
learning to throw a new type of baseball pitch) in such a way needed to main-
tain or improve their high skill level. In situations where new task constraints
are explicitly introduced as a means to disrupt or suspend automated procedures
and allow performance patterns to be altered, experts should be able to attend
to performance in a way that permits them to make desired performance
corrections. Furthermore, once experts start attending to task performance,

their expert knowledge may allow them to remember more of what they are attending to than novices; not less as the pattern of data seen above in which experts are attempting to achieve high-level performance by relying on their well-practised procedures.

In order to explore this kind of situation, Beilock and Carr (2001) had novice and experienced golfers perform the same putting task as described above, with the exception that a specially constructed 'funny putter' was substituted for the regular golf putter. The funny putter consisted of a regular putter head attached to an 's' shaped and arbitrarily weighted putter shaft. The design of the funny putter was intended to require experienced golfers to alter their well-practiced putting form in order to compensate for the distorted club, perhaps forcing them to allocate attention to the new skill execution processes in much the same way as they might need to be able to do in a practice situation designed to revise or correct a component process of performance.

If the 'funny putter' prompts attention to execution, then experienced individuals' memories for specific instances of performance may be enhanced, as the funny putter is now directing the attention needed to create episodic performance memories back to controlling the step-by-step execution of the putting skill. In contrast, the funny putter should not affect novice performers in the same way as more experienced golfers. Novices are already thought to attend to performance (Fitts, 1964; Fitts and Posner, 1967), and have not yet adapted to putting under normal conditions, performance should not be drastically influenced by an altered putting environment.

Comparisons of putting performance across the novice and experienced golfers demonstrated that the type of putter did not significantly affect novices' putting accuracy, although novices using the funny putter did generally perform at a slightly lower level than their regular putter counterparts (Figure 14.2). This result is not surprising considering that the novice golfers were not experienced with either type of putter prior to the experiment. Experts' putting accuracy was superior to novices and was more accurate with the regular putter than with the funny putter, especially during the practice condition and post-tests.

Although experienced golfers using the funny putter performed at a lower level than regular putter experts during the pre-test, this difference was not as large as in the later practice and post-test conditions. It may be that in the pre-test condition, expert golfers, regardless of putter type, were adjusting to the novel experimental demands of having to land the ball on the target rather than in a hole. Thus, experts using the regular putter were not performing up to their potential in the pre-test. The difference between the regular and funny putter experts widened quickly however, as practice proceeded. Due to the fact that experienced golfers often encounter novel putting greens, and must adapt to these situations in order to maintain a low handicap, it is not surprising the experts using the regular putter were able to rapidly adjust to our indoor green. In contrast, as can be seen from Figure 14.2, those experts using the funny putter were unable to adapt to the demands of the new putter within the time frame of the experiment, performing at a similar level of accuracy across experimental conditions.
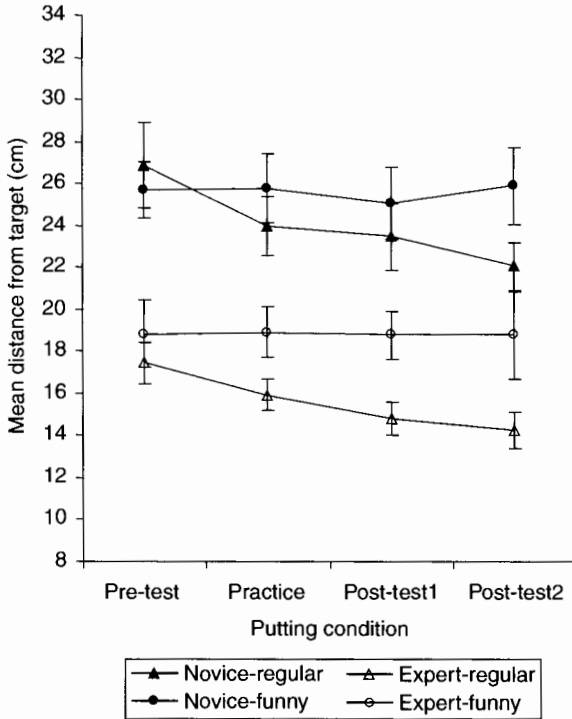
Figure 14.2 Mean distance (cm) from the target that the ball stopped after each putt in the pre-test condition (pre-test), practice condition (practice), first post-test condition (post-test1), and second post-test condition (post-test2) for each group. Error bars represent standard errors. Adapted from Beilock and Carr (2001).

In terms of the memory protocols, while novices, regardless of the type of putter, produced shorter generic descriptions of putting and longer episodic memory protocols than experienced golfers using the regular putter, this was not the case for the experts using the funny putter. As can be seen in Figure 14.1, experts using the funny putter provided the most elaborated generic and episodic protocols. From our theoretical perspective, attention to the novel constraints of the funny putter prompted these golfers to allocate more attention to skill execution processes, enhancing generic descriptions and leaving explicit episodic memory traces of performance. Additionally, the episodic recollections of the experts using the funny putter were longer than their generic descriptions, not shorter as produced by the regular putter experts. Thus, when a proceduralized skill is disrupted by the imposition of novel task demands, 'expertise-induced amnesia' disappears. Furthermore, once experts start attending to task performance, their expert knowledge allows them to remember more of what they are attending to than novices. Note that it is not an easy thing for an expert to achieve this level of attention to the step-by-step control of performance. Consider again the

second episodic memory protocol of experts using the regular putter – the results shown in Figure 14.1. Despite the fact that these experts had just experienced the first memory test and were warned that the second test was coming, they still did not recall as much about their putts as the novices. Therefore, simply wanting to pay attention and to remember, or knowing that this is expected, may not be enough to overcome expertise-induced amnesia.

In an attempt to further explore memory protocols across putter type (i.e. regular versus funny putter) and skill level (i.e. novice versus experienced golfers), we performed a qualitative analysis of the type of putting steps that individuals remembered and compared these steps across the generic and first episodic memory protocols. Memory protocol steps were divided into three categories: assessment or planning referred to deciding how to approach a particular putt, what problems it might present, and what properties the putt ought to have. Examples are 'read the green', 'read the line' (from the ball to the hole or target), 'focus on the line', and 'visualize the force needed to hit the ball'. Mechanics or execution referred to the components of the mechanical act that implement the putt. Examples are 'grip the putter with your right hand on top of your left', 'bring the club straight back', and 'accelerate through the ball', all of which deal with the effectors and the kinesthetic movements of the effectors required to implement a putt. Finally, ball destinations or outcomes referred to where the ball stopped or landed and hence to the degree of success.

As can be seen in Figure 14.3, assessment steps decreased in number from the generic to episodic protocol for the two experienced groups, regardless of the type of putter. The two novice groups showed similar numbers of assessment steps in their generic and episodic protocols. In terms of mechanical steps, the experienced golfers using the funny putter gave more steps that referred to putting mechanics than any other group. The experienced golfers with the regular putter highlighted fewer steps relating to mechanics. The two novice groups did not differ and fell between the two groups of experts with regard to the number of mechanics reported.

It is interesting to note that while expert golfers using either the regular or funny putter included fewer assessment steps in their episodic protocols than in their generic descriptions, a different pattern emerged for mechanics. Experienced golfers using the regular putter highlighted fewer steps related to mechanics in their episodic protocols in comparison to their generic descriptions. The funny putter experienced golfers provided more steps which related to mechanics (see Figure 14.3). The design of the funny putter was intended to specifically distort the mechanical act of implementing the putt. As a result, attention to the assessment and planning of the putt should not have been significantly influenced by putter type. The fact that the experienced golfers did not differ in terms of assessment steps included in their episodic memory protocols as a function of type of putter, yet did vary in their accounts of the mechanical actions involved in putting, is consistent with the notion that increased attention to performance as a result of novel task constraints serves specifically to enhance episodic memories for the altered parameters and components of skill execution.

In conclusion, the memory data reviewed above suggests that novices have sparse general putting knowledge, yet detailed episodic memories for performance
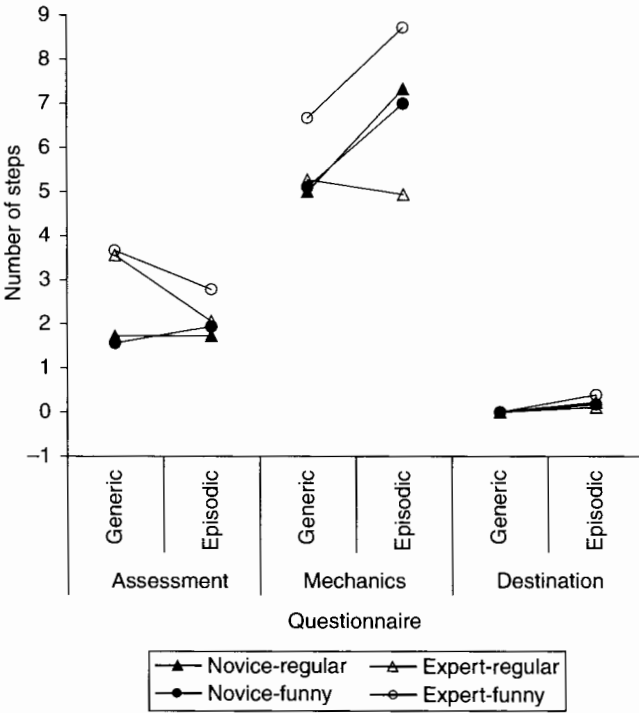
Figure 14.3 Mean number of steps in each category for the generic and first episodic questionnaire for each group. Adapted from Beilock and Carr (2001).

processes and procedures. Experts show the opposite pattern. Expert golfers have high levels of general knowledge but reduced episodic memories (i.e. 'expertise-induced amnesia') for heavily practiced phases of task activity in familiar skill execution situations (e.g. when using the regular putter). However, this pattern changes with the introduction of novel task constraints (i.e. the 'funny putter') that force experts to attend to the step-by-step processes of performance.

Attention and skill acquisition

The notion that different cognitive processes underlie various stages of skill acquisition, with a trend toward increased proceduralization at higher levels of expertise, not only carries implications for the quality of experts' and novices' generic and episodic performance memories, but also for the types of attentional manipulations that may influence performance at different levels of learning. Because novices must devote attentional capacity to task performance in ways that experts do not (Fitts, 1964; Fitts and Posner, 1967), novice and expert performers may be differentially affected by conditions that either draw attention

away from, or toward, skill execution. Specifically, the capacity-demanding performance of novices may not afford these individuals the attentional resources necessary to devote to secondary task demands if required by the situation. However, the proceduralized performances of experts, that normally run outside of working memory, should leave attention available for the processing of other aspects of the stimulus situation, even stimuli not related at all to primary skill performance (Allport *et al.*, 1972; Leavitt, 1979; Smith and Chamberlin, 1992). Because the well-practised and proceduralized components of expert performance are not explicitly attended in real time, however, attention prompted toward skill execution may actually serve to break down or disrupt automated performance processes that normally run without such explicit attention or awareness (Beilock and Carr, 2001; Beilock *et al.*, 2002a; Lewis and Linder, 1997; Masters, 1992; Masters *et al.*, 1993; Marchant and Wang, 2001). In contrast, the novice, who must attend to the steps of skill execution in order to succeed, might not be harmed or could perhaps be helped by conditions that focus attention more squarely on the skill and prevent it from wandering.

In order to explore these possibilities, we conducted another putting study in which novice and experienced golfers performed the same task as described above under either dual-task or skill-focused attention conditions (see Beilock *et al.*, 2003). The dual-task attention condition involved putting while simultaneously listening to a series of recorded tones being played from a tape recorder. Participants were instructed to monitor the tones carefully, and each time they heard a specified target tone, to say the word 'tone' out loud. Tones (500 milliseconds each) occurred at a random time period once within every 2-seconds time interval. The target tone occurred randomly, once every four tones on average. In the skill-focused attention condition, participants were instructed to attend to a particular component of their golf putting swing. Specifically, individuals were instructed to monitor their swing and attempt to keep the club head straight, travelling towards the target along the same path as the ball, during the swing and follow through. Participants were informed that in order to assure that they were attending to the motion of the swing during the putt, they should say the word 'straight' out loud as they made contact with the ball. This particular component of the putting swing was chosen as the basis for the skill-focused manipulation because a straight club head is thought to be an important component of a successful golf putt (Jones *et al.*, 1998).

Individuals performed thirty-five initial putts, designed to familiarize them with our altered putting task requiring individuals to land the ball on a target rather than in a hole. Participants then took twenty practice putts in a single-task environment, twenty putts in a dual-task attention condition and twenty putts in a skill-focused attention condition. The order of the two attention conditions was counterbalanced across participants. The mean distance from the target that the ball landed after each putt for the twenty putts in the skill-focused and dual-task conditions was used as the measure of that condition's putting performance.

Novice golfers performed significantly worse in the dual-task condition in comparison to the skill-focused condition, as illustrated in Figure 14.4. Experienced
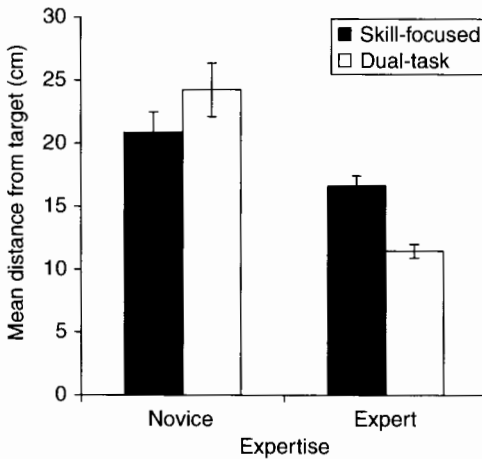
Figure 14.4 Mean distance (cm) from the centre of the target that the ball stopped after each putt in the skill-focused and dual-task conditions for the novice and experienced golfers. Error bars represent standard errors. Adapted from Beilock *et al.* (in press).

golfers showed the opposite pattern, putting more accurately in the dual-task than skill-focused attention condition. This pattern of results supports the notion that the control structures driving performance differ as a function of skill level. Novice performance is thought to be attended in real time (Fitts, 1964; Fitts and Posner, 1967). Thus, dual-task situations that draw attention away from performance harm execution in comparison to conditions that prompt attention to online control. Experienced performers, on the other hand, are thought not to explicitly attend step-by-step execution. Consequently, attentional capacity is left over to devote to secondary task demands, if the situation requires, without significantly disrupting primary skill execution. However, if experts are asked to attend to performance in a way that they are not accustomed (e.g. the skill-focused condition), this attention serves to break down or disrupt execution, resulting in a less than optimal skill outcome. These negative effects of enhanced attention to skilled performance can not only be seen in complex skills such as golf putting, but in more basic skills we use everyday. For example, Wulf and colleagues have suggested that directing performers' attention to their movements through 'internal focus' feedback on a dynamic balance task interferes with the automated control processes that usually control balance movements outside of conscious scrutiny (Wulf and Prinz, 2001).

Implications for practice and instruction

The findings outlined in this chapter suggest that the effects of attention on performance are dependent on an individual's skill level. This has obvious

implications for skill acquisition at lower levels of learning, as well as for performance at high levels of task proficiency across a variety of attention-demanding and pressure situations.

Attention and performance

Given the attentional demands of newly acquired performances, for example, it may be beneficial to limit the number of cues novices must attend to as they are learning to perform a specific task. This type of simplification for the sake of learning is often characterized as part-task practice in the motor learning literature (Magill, 1998) and has been proposed rather generally as a means to manage the heavy attention demands of learning new skills, whether sensori-motor or intellectual (e.g. Carlson *et al.*, 1990; Carr, 1984; Mattoon, 1994; Whaley and Fisk, 1993).

There are a number of different ways of instantiating part-task training regimens. Wightman and Lintern (1985) have suggested three: *fractionization* involves practicing separate components of an entire skill. *Simplification* is characterized by reducing the difficulty of the skill and practicing it in a unitary fashion. In a juggling task, for example, one might practice juggling with scarves prior to shifting over to flaming torches as a means to reduce the overall complexity of the juggling skill execution. Finally, *segmentation* involves separating a skill into separate components and progressively adding new components to skill practice. The segmentation approach is often seen in 'real-world' sports contexts.

In baseball, for example, children first learn to play 't-ball'. In this simplified form of baseball, a stationary 'tee' is substituted for a pitcher and the child's goal is to hit the ball off of the 'tee', which supports the ball at about waist height. Hitting the ball from the 'tee' eliminates the pitcher and the moving ball, limiting the number of stimuli that must be attended to by the novice batter. Given that novices are harmed by situations in which they must attend to many concurrent stimuli (e.g. the dual-task situations described above), the single-task t-ball situation allows the unpractised batter the attentional resources necessary to devote to learning an efficient and consistent swing pattern. Drawing on theories of skill acquisition and automaticity, with extended practice the swing may become proceduralized, freeing up attentional resources to be devoted to other aspects of the game situation. At higher levels of practice, a baseball player is able to successfully bat from a real pitcher as attention is not required for the step-by-step control of the swing and is thus available for attending to other components of play, such as tracking the movements of the pitcher and the ball. As we have seen above, attention to swinging the bat at this later stage of learning may not only be unnecessary, it may actually be detrimental to that aspect of performance. That is, attempting to explicitly attend to the step-by-step execution of a well-learned swing may actually hurt performance by slowing down or disrupting the proceduralized or automated swing movement. Theories of 'choking under pressure', to which we will return momentarily, propose just this effect.

At high levels of skill, however, there may be situations in which attention to performance is beneficial. When the goal is to explicitly alter performance processes in order to change execution parameters for the purpose of improving long-term skill performance, or in an attempt to achieve a different outcome, attention to performance may be beneficial. Attending to performance in this fashion has been proposed to be an important component of deliberate practice (Ericsson *et al.*, 1993), and may benefit both novice and experienced performers. In this type of situation, one might imagine that an experienced baseball player is interested in altering their swing pattern. In order to achieve this goal, the player must explicitly attend to the specific parameters of the swing. Because this process requires attention, the baseball player may not have the resources necessary to effectively deal with other stimuli in the environment (such as inconsistent or unpredictable pitches).

Furthermore, the act of paying attention may in itself be difficult for the expert. Turning back to the first experiment described in this chapter (Beilock and Carr, 2001), even when experts putting under normal conditions (i.e. experts using the regular putter) knew they were going to be expected to recall their memories of putting performance (in the second episodic memory test), they still showed a degree of expertise-induced amnesia. Because episodic performance memories are dependent on attention at encoding, this lack of memory suggests that even when experts are instructed to attend to their performance and are trying to follow the instructions, they may have difficulty doing so. Our baseball player interested in altering swing parameters then, may also need to expend additional executive resources concentrating and maintaining attentional focus on step-by-step control. To deal with these attentional demands, the batter may use a machine that produces predictable pitches, thereby reducing the total amount of information to be attended in the situation and affording the player the attention necessary to devote to correcting the swing process. Once the swing is corrected and the control structures of performance return to a proceduralized state, the batter may once again have the attention necessary to devote to a live pitcher, while ignoring or not explicitly attending to the more mechanical aspects of swinging the bat.

Choking under pressure

When the goal is to alter execution parameters, attention to performance may be beneficial. However, when optimal real-time performance is desired, attention to step-by-step execution may instead serve to slow, disrupt or dismantle high-level performance. 'Explicit monitoring' or 'execution focus' theories of choking under pressure suggest that sub-optimal performance of a well-learned skill under pressure results from an attempt to exert explicit monitoring and control on proceduralized knowledge that is best run-off as an uninterrupted and unanalysed structure (Baumeister, 1984; Beilock and Carr, 2001; Beilock *et al.*, 2002b; Lewis and Linder, 1997; Masters, 1992, 2000). Thus, high-level skills based on an automated or proceduralized skill representation may be more susceptible to the

negative consequences of performance pressure than less practiced performances. This is due to the fact that the former, but not the latter, operates largely outside of working memory and pressure-induced attention may harm processes that are normally devoid of step-by-step attentional control.

Beilock and Carr (2001) have found support for the notion that well-learned, but not novice, sensori-motor skill execution is susceptible to performance decrements under pressure via this mechanism of inappropriate explicit monitoring or execution focus. Participants learned a golf putting skill to a high-level and were exposed to a high pressure situation both early and late in practice. Early in practice, pressure to do well actually facilitated performance. At later stages of learning, performance decrements under pressure emerged. It appears that the proceduralized performances of experts are negatively affected by performance pressure. Novice skill execution, however, is not harmed by pressure-induced attention to execution as less skilled performance is already explicitly attended in real time. This finding is consistent with Marchant and Wang's (2001) assertion that most of the evidence for choking under pressure has been derived from well-learned sensori-motor tasks that automate via proceduralization with extended practice.

Support for explicit monitoring theories can also be seen in training studies that serve to inoculate individuals against the negative effects of performance pressure by adapting them (during training) to the type of explicit attention to execution that pressure is thought to induce. For example, both Beilock and Carr (2001) and Lewis and Linder (1997) have found that learning a golf putting skill in a self-awareness-heightened environment inoculates individuals against the negative effects of performance pressure at high levels of practice. In both of these studies, participants were trained on a golf putting task under either a self-awareness condition (in which individuals putted while being videotaped for later analysis by golf professionals) or under a normal, single-task condition and then exposed to a high-pressure situation. The self-awareness manipulation was designed to expose performers to having attention called to themselves and their performance in a way intended to induce explicit monitoring of skill execution. In both the studies by Beilock and Carr and Lewis and Linder, it was found that pressure caused choking in those individuals who had not been adapted to self-awareness, a finding consistent with explicit monitoring theories. Furthermore, in the Lewis and Linder study, it was found that the introduction of a secondary task (counting backward from 100) while performing under pressure helped to alleviate performance decrements (for confirmatory data, see Mullen and Hardy, 2000). Because the secondary task served to prevent the pressure-induced instantiation of maladaptive explicit attention to automated or proceduralized performance processes, choking under pressure was alleviated.

Choking under pressure at high skill levels, then, may be alleviated by the instantiation of a secondary task during the actual high-pressure performance. A 'key word', that takes a golfer's mind off of the step-by-step mechanics involved in a simple 3-foot putt, or a song that a batter hums while up to bat, may prevent the type of maladaptive explicit attentional control that performance pressure is

thought to induce. Further work on the judicious adoption of such self-distraction techniques seems quite worthwhile.

Summary and conclusions

While overt performance is one component that separates novice from well-learned skill execution, the cognitive control structures governing execution appear to distinguish unpractised from high level skills as well. Theories of skill acquisition and automaticity have proposed that distinct cognitive processes are involved at different stages of skill execution. Early in learning, individuals are thought to attend to the step-by-step processes of performance. However, once a high level of performance has been achieved, constant online attentional control may not be necessary (Anderson, 1983, 1993; Fitts and Posner, 1967; Logan, 1988).

While a progression from a declarative knowledge base to proceduralization is a powerful conception of the cognitive processes governing skill acquisition, alternative explanations of skill acquisition are available and have merit. Some of these alternatives propose differences in the type of representation that underlies skills early in learning, with implications for the type of training conditions that are beneficial to the novice. For example, it has been suggested that explicit declarative knowledge is not necessary in the acquisition of highly structured sequential knowledge analogous to the syntax of language production. Research in artificial grammar, for example, has demonstrated that in some cases learning may benefit from a lack of explicit instruction (for a review, see Reber, 1989). Masters has exported such an argument to the domain of sensori-motor skill execution (e.g. Masters, 2000).

Additional alternatives to the conceptualization of proceduralization have also been suggested as a means to describe well-learned performance. Logan (1988) has proposed an instance-based theory of automaticity in which highly practised performance is based on the direct retrieval of specific past episodes or instances of execution from long-term memory, rather than relying on a procedure or programme that can generate new performances in an effective, efficient manner. Performance based on retrieval of instances is thought to differ from earlier, less practiced stages of execution in which problem solutions and task performances are derived through the implementation of an explicit rule-based algorithm. It is not likely, however, that sensori-motor skill execution is governed by instance-based answer retrieval, as instance-based theories of automaticity do not allow for transfer of performance to novel situations, something that can occur in practiced sensori-motor skills (Koh and Meyer, 1991), albeit often with some cost. In our laboratory, we are currently comparing instance-based (e.g. mathematical problem solving) versus proceduralized skills (e.g. golf putting) in terms of their susceptibility to performance decrements in high pressure and attention-demanding situations (Beilock *et al.*, 2002b).

In conclusion, in this chapter we have presented evidence concerning the differential attentional demands and changing memory structures that underlie

performance at various skill levels. The present findings highlight the notion that one must look beyond overt performance measures in order to truly understand the variables mediating skill execution across levels of expertise. A continued exploration of the processes and procedures underlying performance at different levels of learning will not only serve to enhance our understanding of the skill acquisition process, but will add to our knowledge base concerning the ability to maintain high-level performance in situations where incentives for optimal task performance are at a maximum.

References

Abernethy, B., Thomas, K. T. and Thomas, J. T. (1993). Strategies for improving understanding of motor expertise [or mistakes we have made and things we have learned!!]. In J. L. Starkes and F. Allard (Eds), *Cognitive issues in motor expertise* (pp. 317–356). Amsterdam: Elsevier Science.

Allard, F. and Starkes, J. L. (1991). Motor-skill experts in sports, dance and other domains. In K. A. Ericsson and J. Smith (Eds), *Toward a general theory of expertise* (pp. 126–152). Cambridge: Cambridge University press.

Allport, D. A., Antonis, B. and Reynolds, P. (1972). On the division of attention: a disproof of the single channel hypothesis. *Quarterly Journal of Experimental Psychology*, 24, 225–235.

Anderson, J. R. (1982). Acquisition of a cognitive skill. *Psychological Review*, 89, 369–406.

Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard University press.

Anderson, J. R. (1993). *Rules of mind*. Hillsdale, NJ: Erlbaum.

Anderson, J. R. and Lebiere, C. (1998). *The atomic components of thought*. Mahwah, NJ: Erlbaum.

Baumeister, R. F. (1984). Choking under pressure: self-consciousness and paradoxical effects of incentives on skillful performance. *Journal of Personality and Social Psychology*, 46, 610–620.

Beilock, S. L. and Carr, T. H. (2001). On the fragility of skilled performance: what governs choking under pressure? *Journal of Experimental Psychology: General*, 130, 701–725.

Beilock, S. L., Carr, T. H., MacMahon, C. and Starkes, J. L. (2002a). When paying attention becomes counterproductive: impact of divided versus skill-focused attention on novice and experienced performance of sensorymotor skills. *Journal of Experimental Psychology: Applied*, 8, 6–16.

Beilock, S. L., Feltz, D. L. and Carr, T. H. (2002b). More on the fragility of skilled performance: choking under pressure is caused by different mechanisms in cognitive versus sensorymotor skills. Poster presented at the Annual Meeting of the Psychonomic Society. Kansas City, Missouri.

Beilock, S. L., Wierenga, S. A. and Carr, T. H. (2002c). Expertise, attention, and memory in sensorymotor skill execution: impact of novel task constraints on dual-task performance and episodic memory. *The Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, 55, 1211–1240.

Beilock, S. L., Bertenthal, B. I., McCoy, A. M. and Carr, T. H. (in press). Haste does not always make waste: expertise, direction of attention, and speed versus accuracy in performing sensorymotor skills. *Psychonomic Bulletin and Review*.

Brown, T. L. and Carr, T. H. (1989). Automaticity in skill acquisition: mechanisms for reducing interference in concurrent performance. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 686–700.

Bryan, W. L. and Harter, N. (1899). Studies on the telegraphic language: the acquisition of a hierarchy of habits. *Psychological Review*, 6, 345–375.

Carlson, R. A., Khoo, B. H. and Elliott, R. G. (1990). Component practice and exposure to a problem-solving context. *Human Factors*, 32, 267–286.

Carr, T. H. (1984) Attention, skill, and intelligence: some speculations on extreme individual differences in human performance. In P. Brooks, C. McCauley and R. D. Sperber (Eds), *Learning, cognition, and mental retardation*. Hillsdale, NJ: Lawrence Erlbaum.

Chase, W. G. and Simon, H. A. (1973). Perception in chess. *Cognitive Psychology*, 4, 55–81.

Craik, F. M., Govini, R., Naveh-Benjamin, M. and Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology: General*, 125, 159–180.

De Groot, A. (1978). *Thought and choice in chess*. The Hague: Mouton (original work published in 1946).

Ericsson, K. A., Krampe, R. T. and Tesch-Romer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review*, 100, 363–406.

Ericsson, K. A. and Polson, P. G. (1988). An experimental analysis of the mechanisms of a memory skill. *Journal of Experimental Psychology: Learning, Memory & Cognition*, 14, 305–316.

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W. Melton (Ed.), *Categories of human learning*. New York: Academic Press.

Fitts, P. M. and Posner, M. 1. (1967). *Human performance*. Belmont, CA: Brooks/Cole.

Jones, B. T., Davis, M., Crenshaw, B., Behar, T. and Davis, M. (1998). *Classic instruction in golf*. New York: Broadway.

Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman and J. P. Thomas (Eds), *Handbook of perception and human performance*, Vol. 7. New York: John Wiley.

Keele, S. W. and Summers, J. J. (1976). The structure of motor programs. In G. E. Stelmach (Ed.), *Motor control: issues and trends* (pp. 109–142). New York: Academic Press.

Koh, K. and Meyer, D. E. (1991). Function learning: induction of continuous stimulus–response relations. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 17, 811–836.

Leavitt, J. (1979). Cognitive demands of skating and stick handling in ice hockey. *Canadian Journal of Applied Sport Sciences*, 4, 46–55.

Lewis, B. and Linder, D. (1997). Thinking about choking? attentional processes and paradoxical performance. *Personality and Social Psychology Bulletin*, 23, 937–944.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, 95, 492–527.

Magill, R. A. (1998). *Motor learning concepts and applications*. Boston, MA: McGraw-Hill.

Marchant, D., and Wang, J. (2001). Choking: Current Issues in Theory and Practice. Paper presented at the 10th World Congress of Sport Psychology. Skiathos, Greece.

Masters, R. S. W. (1992). Knowledge, knerves and know-how: the role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology*, 83, 343–358.

Masters, R. S. W. (2000). Theoretical aspects of implicit learning in sport. *International Journal of Sport Psychology*, 31, 530–541.

Masters, R. S. W., Polman, R. C. J. and Hammond, N. V. (1993). 'Reinvestment': a dimension of personality implicated in skill breakdown under pressure. *Personality and Individual Differences*, 14, 655–666.

Mattoon, J. S. (1994). Designing instructional simulations. Effects of instructional control and type of training task on developing display-interpretation skills. *International Journal of Aviation Psychology*, 4, 189–209.

McKeithen, K. B., Reitman, J. S., Reuter, H. H. and Hirtle, S. C. (1981). Knowledge organization and skill differences in computer programmers. *Cognitive Psychology*, 13, 307–325.

Mullen, R. and Hardy, L. (2000). State anxiety and motor performance: testing the conscious processing hypothesis. *Journal of Sports Sciences*, 18, 785–799.

Naveh-Benjamin, M., Craik, F. I., Guez, J. and Dori, H. (1998). Effects of divided attention on encoding and retrieval processes in human memory: further support for an asymmetry. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 24, 1091–1104.

Proctor, R. W. and Dutta, A. (1995). *Skill acquisition and human performance*. Thousand Oaks, CA: Sage.

Raichle, M. E., Fiez, J. A., Videen, T. O., Macleod, A. M. K., Pardo, J. V., Fox, P. T. and Petersen, S. E. (1994). Practice-related changes in human brain functional-anatomy during nonmotor learning. *Cerebral Cortex*, 4, 8–26.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General*, 118, 219–235.

Reimann, P. and Chi, M. T. (1989). Human expertise in complex problem solving. In K. J. Gilhooly (Ed.), *Human machine and problem-solving* (pp. 161–189). New York: Plenum.

Smith, M. D. and Chamberlin, C. J. (1992). Effect of adding cognitively demanding tasks on soccer skill performance. *Perceptual and Motor Skills*, 75, 955–961.

Staszewski, J. J. (1988). Skilled memory and expert mental calculation. In M. T. H. Chi, R. Glaser and M. J. Farr (Eds), *The nature of expertise* (pp. 71–128). Hillsdale, NJ: Lawrence Erlbaum Associates.

Starkes, J. L., Deakin, J. M., Lindley, S. and Crisp, F. (1987). Motor versus verbal recall of ballet sequences by young expert dancers. *Journal of Sport Psychology*, 9, 222–230.

Whaley, C. and Fisk, A. D. (1993). Effects of part-task training on memory set unitization and retention of memory-dependent skilled search. *Human Factors*, 35, 639–652.

Wightman, D. C. and Lintern, G. (1985). Part-task training strategies for tracking and manual control. *Human Factors*, 27, 267–283.

Wulf, G. and Prinz, W. (2001). Directing attention to movement effects enhances learning: a review. *Psychonomic Bulletin and Review*, 8, 648–660.