Cognition in Skilled Action: Meshed Control and the Varieties of Skill Experience

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Abstract: We present a synthetic theory of skilled action which proposes that cognitive processes make an important contribution to almost all skilled action, contrary to influential views that many skills are performed largely automatically. Cognitive control is focused on strategic aspects of performance, and plays a greater role as difficulty increases. We offer an analysis of various forms of skill experience and show that the theory provides a better explanation for the full set of these experiences than automatic theories. We further show that the theory can explain experimental evidence for skill automaticity, including evidence that secondary tasks do not interfere with expert performance, and evidence that experts have reduced memory for performance of sensorimotor skills.

Introduction

Influential characterizations of skill acquisition in both psychology and philosophy depict it as a progression from an initial cognitive phase to an expert phase in which performance is largely automatic (Fitts and Posner, 1967; Dreyfus and Dreyfus, 1986). The enduring appeal of this picture is illustrated in Schmidt and Wrisberg's (2008) textbook account of motor skill learning, which describes skill learning as a progression to an autonomous stage in which learners 'are able to produce their actions almost automatically with little or no attention' (p. 202). This seems to suggest that higher cognition typically plays no role in skill control, and Dreyfus and Dreyfus are explicit on this point, saying that '*When things are proceeding normally, experts don't solve problems and don't make decisions; they do what normally works*' (pp. 30–1, italics in original). The idea that advanced skills are non-cognitive is also prevalent amongst sports practitioners and in popular culture. To give just one recent example, the elite Sri Lankan cricketer Kumar Sangakkara has said that 'Basically in batting, you have to be mindless. You've done all the practice, you have your muscle memory and your reflexes are more than quick to deal with any kind of delivery. You've got to let your body do all those things by itself without letting your mind take control' (Sadikot, 2014). Such claims have been taken by some philosophers

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as evidence that expert performance is automatic. Brownstein (2014), for instance, uses reports like this as a central component of an argument that much skilled action is unreflective, in the sense that it occurs with little conscious awareness of what is being done. Like Dreyfus (2013), Brownstein claims that this lack of awareness is sufficiently profound that experts will often be unable to explain their actions after the fact. Recently, though, a number of philosophers and psychologists have reacted against this kind of view: Sutton (2007), Montero (2010), Sutton *et al.* (2011), Stanley and Krakauer (2013), Papineau (2013), Fridland (2014) and Toner *et al.* (2014) all criticize the mindless view of expert performance and begin to make the case that cognition does make some important contribution to skilled action.

Our intention here is to develop a broadly-based, systematic theory of skill learning and control that clearly articulates the idea that cognitive and automatic processes both make a major contribution to skilled action. The basic idea on which this theory is based is that cognitive control is not eliminated in advanced skill, but is rather shifted primarily to higher-level action control. This idea is not new—it can be found in varied forms in prior work. Thus, although Schmidt and Wrisberg (2008) characterize skill learning as a progression to increasingly automatic action production, they *also* say that increased automaticity in motor production and sensory analysis 'frees the best performers to engage in higher-order cognitive activities, such as split-second shifts in strategy during a basketball game or spontaneous adjustments in the form or style of a movement in dance or in figure skating' (p. 202). Suggestions of this kind of shift in the role of cognitive control can be found in Bryan and Harter's (1899) study of skill learning in telegraphers; they describe a series of stages in which the learner first 'hustles for the letters', is then 'after words', then phrases and sentences, and finally is able to focus on the meaning of the message (p. 352). There is a hint that Fitts and Posner may have believed that it is primarily component processes which automate (1967, p. 14), and Logan (1985) and Jonides *et al.* (1985) explicitly argued that overall action control does not automate. Vallacher and Wegner (1987) gave an account of a shift in attentional focus during skill learning similar to that of Bryan and Harter. They argued that in the initial stages of learning the difficulty of the actions results in a focus on low-level aspects of the actions, while improving mastery involves a 'chunking' of actions into larger action units and a conscious focus on high-level aspects of the actions (pp. 7–8).

But if the basic idea is not uncommon, it has also not yet been systematically developed. In our view there are good reasons to think that higher cognition does make substantial contributions to advanced skills, and a theory of skill learning and control must clearly recognize this. Such a theory would address not only the automation of aspects of control but also the shift in the role of cognitive control, its main processes, and the relations between automatic and cognitive control in performance. This theory should be synthetic, framed at the same level of generality as the theories of Fitts and Posner and Dreyfus and Dreyfus, and draw on a wide range of evidence across multiple disciplines. In this article we develop the basic structure of the account, show how it can accommodate several important strands of experimental skill research, and suggest avenues for further empirical investigation.

Our aim is to construct an inclusive and systematic framework. We begin by delineating the space of theoretical options in a way that is deliberately coarse-grained, identifying a basic set of theoretical possibilities and locating our account within this space. This leaves aside the fine-grained structure of extant positions but allows us to identify general issues that any skill theory should address. We next describe a range of types of skill experience that are suggestive of either automatic or cognitive control, and show that our account provides a better overall account of these types of experience than does an account that sees skill control as automatic. This analysis is not intended to provide definitive support—it rather helps to clarify our account and identify key issues and forms of evidence. We then show the value of the account by using it to interpret and evaluate several extant positions with respect to skill learning and control. Dreyfus (1997) defends his account against contrary evidence concerning expert decision-making, and we use our analysis to highlight conceptual weaknesses in Dreyfus's position that undermine his attempt to downplay the significance of this evidence. An influential strand of research in complex motor skills has produced evidence that has been taken to show that skills like dribbling a hockey puck and putting a golf ball are automatic. We use our framework to argue that this interpretation relies on questionable assumptions about real-world skill performance, and suggest an experimental approach that would provide a better test of the respective contributions of automatic and cognitive processes to skill performance.

1. Cognitive and Automatic Control: Dual Process Versus System Views

Before discussing their respective roles in skill we need an initial characterization of cognitive and automatic control. The term 'cognitive control' comes from cognitive psychology, and broadly refers to control associated with conscious awareness and intentionality. Posner and Snyder (1975) proposed that cognitive control is the product of a flexible, limited capacity system, which through conscious attention establishes a program or strategy for processing information. They operationally characterized automatic control as occurring without attention, without conscious awareness, and without producing interference with other ongoing mental activity (p. 56).

Recent research has introduced a number of complexities, however, and we can distinguish between two broad conceptions of the nature of, and relations between, cognitive and automatic control. The differences between these conceptions have important consequences for skill theory. The first is relatively straightforward, and close to the classical view outlined by Posner and Snyder. For reference we'll call it the *dual process view*. According to this conception there is a fairly robust contrast between processes that are rapid and autonomous, and tend to govern responses when there is no higher cognitive intervention, and effortful explicit (conscious) reasoning processes that are strongly dependent on working memory. This conception has been codified in dual-process accounts of cognitive architecture, recently defended by Evans and Stanovich (2013).

The second conception is discernible in a number of different strands of research on cognitive and automatic control. This view has two key elements: (i) a stronger emphasis on cognitive control as the product of an executive system, which involves a broader understanding of the processes involved in cognitive control, and (ii) a more complex and nuanced understanding of automaticity. We'll call this the *systems view* to flag the fact that it involves a shift towards an understanding of cognitive and automatic control in terms of systemic interactions and away from a simple contrast between two kinds of processes.

As noted, Posner and Snyder associated cognitive control with the operation of a flexible executive system, and this is also a feature of contemporary dual process views (Evans and Stanovich, 2013). But dual process views nevertheless frame the contrast between cognitive and automatic control in terms of two kinds of processes. Conscious reasoning is taken as the paradigmatic form of controlled cognitive process. This contrast breaks down for the systems view: cognitive control, understood in terms of the operation of the executive system, involves a broader range of processes than just conscious reasoning, and many of these processes can show a great deal of automaticity.

More specifically, cognitive neuroscience research on cognitive control has associated it with a neural system that includes the prefrontal and parietal cortices (Miller, 2000; Fuster, 2008). Some of the primary functions that have been associated with cognitive control in this tradition include controlling attention, the active maintenance and processing of information (working memory), the flexible integration of information related to the current situation and activities, setting and switching between goals, establishing an action or task 'set' (a processing configuration for the situation), inhibiting inappropriate responses, forming action plans, decision-making, and problem solving (Miller, 2000; Duncan, 2010). Many of the processes involved in performing these functions are not conscious or only partly conscious. For instance, an individual focused on interpreting the situation may be only partly aware of adopting a particular action set for the situation, and unaware of the inhibition of responses that are incompatible with the task set.

Research on automaticity has seen similar complexification, with greater recognition of rich systemic interactions. Moors and De Houwer (2006) distinguish four main feature clusters linked to automaticity concerning goal and intentions, consciousness, cognitive efficiency, and speed. With respect to goals and intentions, automaticity has been characterized in terms of processes that are uncontrolled, occurring independently of intentions and goals. A strongly automatic process, in this sense, is *autonomous*—roughly, it is not initiated by intentions and it runs to completion without regulation by goals (pp. 307–8). With respect to consciousness, automatic processes have been characterized as non-conscious or involving low awareness. With respect to efficiency, automatic processes have been characterized as attentionally undemanding, and as being experienced as effortless (if they are experienced at all). With respect to speed, automatic processes are characterized as fast, in contrast with cognitive processes that are often assumed to be characteristically slow. Further complexity arises because these various attributes do not group together in a simple way. On some views, intentions and goals can be non-conscious (Bargh, 1990), different aspects of a given process may be conscious or non-conscious, including the input, the process itself, the output, and the consequences, non-conscious processes can be influenced by cognitively controlled processes (and are then not truly autonomous), conscious processes may be fast and subjectively effortless, and so on.

The significance of the distinction between the dual process and systems views for skill theory is that the latter raises new possibilities. The dual process view is central to standard views of skill learning, which posit a qualitative transition from responses based on effortful reasoning to responses based on effortless, autonomous processes (Fitts and Posner, 1967; Dreyfus and Dreyfus, 1986; Schmidt and Wrisberg, 2008). Given that background conception of cognitive and automatic control, this seems plausible. But we'll argue that the systems view lends itself to a more nuanced view of the changes in cognitive and automatic control during skill acquisition.

2. A Sketch of the Basic Options for Skill Theory

We can now delineate some basic options for theories of skill learning and control. Our initial set of contrasts takes the dual process view of cognitive control and automaticity as the conceptual framework; then we describe a different type of skill theory based on the systems view.

Starting with the dual process view, one possibility is that the control of skilled action in normal conditions is almost entirely automatic, a view that we'll call *Automatic.* According to *Automatic,* cognitive control reduces during skill learning and makes no positive contribution to performance with the attainment of advanced skill (Figure 1a). Another possibility, which we'll call *Full Cognitive,* is that there is no reduction, and skilled action is under full 'step-by-step' cognitive control, even at advanced levels of ability (Figure 1b). A third possibility is that automatic processes and cognitive control both contribute to skilled action. We'll call this *Hybrid.* According to *Hybrid,* cognitive control reduces during skill learning as automatic control comes to play an increasing role, but cognitive control continues to make a substantial positive contribution at advanced levels of skill (Figure 1c).

The skill theory presented by Dreyfus and Dreyfus (1986) is the clearest example of an *Automatic* account. Fitts and Posner's account of skill acquisition lends itself to an *Automatic* view of skill, but as we noted in the introduction there is some ambiguity since they may have intended the account to apply to component processes rather than action control as a whole. Schmidt and Wrisberg (2008) focus on automaticity but make claims that align their position with *Hybrid*. From the other direction, Ericsson focuses primarily on the role of cognition in skill and claims that experts resist automation (Ericsson, 2006). Viewed superficially his position would seem to be a version of *Full Cognitive*, but he recognizes that automation plays a role in skill so his position is properly a kind of *Hybrid* account. Despite Shiffrin and Schneider's (1977) influential contrast between controlled and automatic processes,

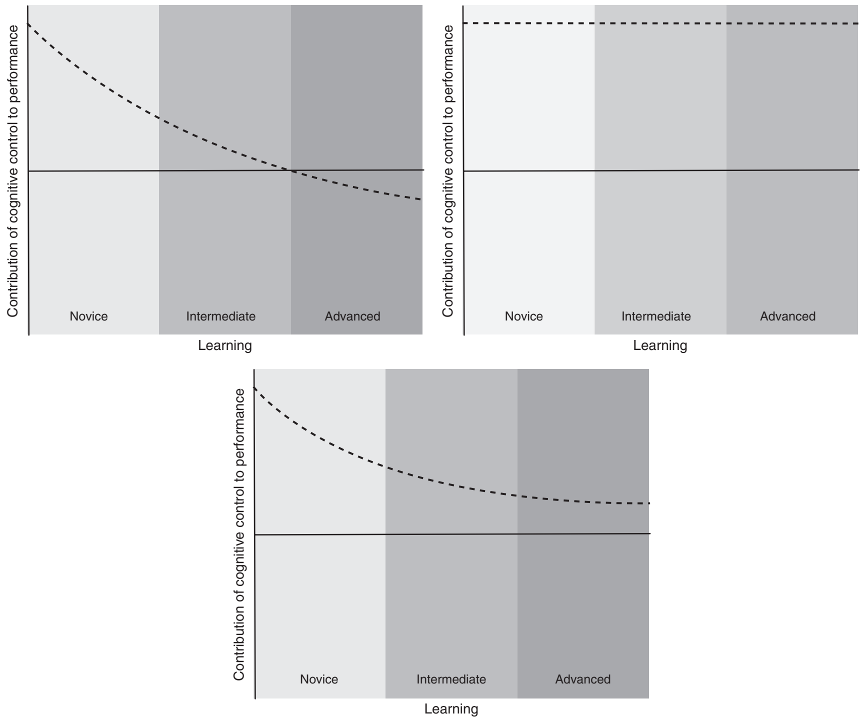

Figure 1 *Cognitive control and experience.*

they too recognized that hybrid control occurs. Thus, they say 'Particularly in complex processing situations, (such as reading), an ongoing mixture of controlled and automatic processing is utilized' (1977, p. 161).

But although many researchers have recognized hybrid control as a possibility, hybrid control hasn't been a focus of investigation in its own right. This leaves it unclear how hybrid control operates and in what circumstances it occurs. There are many possibilities, depending on specific assumptions concerning the nature of controlled and automatic processes, but as a first approximation we distinguish two major versions of *Hybrid*. The first, which we call *Autonomous*, is based on the dual process view, and associates cognitive control with conscious reasoning. In contrast with *Automatic*, *Autonomous* claims that abbreviated forms of reasoning occur in complex, temporally extended skilled action. For example, a soccer player at a particular point in a game may adopt a particular strategy, such as attacking up the left wing to exploit a hole in the defense. The player may also make fast decisions in pursuing this strategy, for instance whether to pass or go around a defender. But these conscious cognitive processes are fleeting, and based on underlying processes that are largely automatic ('intuition'). Moreover, while they produce intentions that guide action, these intentions are at a high level (such as pass to a teammate) and do not play a strong guiding role in the online execution of action, which is largely autonomous.

Such a view seems to be implied by the Schmidt and Wrisberg passage we quoted in the introduction, which associates cognitive control with strategic decisions and occasional adjustments to the overall form of movement in sports like figure skating. A *Hybrid* view of this kind has also found support in philosophy (Papineau, 2013). Beilock and Gray (2007) explicitly identify the role of cognition in performance as being concerned with strategizing, problem solving and decision-making, and further distinguish between skills that require these functions and skills that don't. In the latter group they include skills like golf putting and baseball batting (p. 434). Thus, for *Autonomous*, some skills are performed largely automatically.

We will argue for a different kind of *Hybrid* theory, which we call *Mesh*. Like *Autonomous*, *Mesh* sees a broadly hierarchical division of control responsibilities, with cognitive control usually focused on strategic aspects of performance and automatic processes more concerned with implementation. But unlike *Autonomous*, *Mesh* proposes that controlled and automatic processes are closely integrated in skilled action, and that cognitive control directly influences motor execution in many cases. This difference is in part based on the systems view of cognitive and automatic control described above. One of the cognitive functions associated with cognitive control on the systems view is the flexible integration of information concerning the situation. In skills and expertise research this has been conceptualized as situation awareness, and can involve explicit inferences (Endsley, 1995). But much of the information-integration that contributes to situation awareness is not based on explicit inferences (Miller, 2000; Duncan, 2010), and we assume that situation awareness often occurs without explicit inferential reasoning processes. On the other hand, situation awareness is typically constructed progressively and is closely linked to attentional control. As situation interpretation develops, attention is directed to relevant information which serves to elaborate or revise the interpretation. Situation awareness serves to establish a cognitive and motor configuration appropriate to the context (Duncan, 2010).

These functions contribute to virtually all skilled action, according to *Mesh*, and directly influence action execution. In addition, we claim that skilled actions are often directed by a cognitive action 'gist'. *Autonomous* assumes that intentions are generated in the course of complex skilled action, but it views these as being relatively coarse-grained (e.g. pass the ball). A high level action intention of this kind serves to cue motor processes, but the situational specificity of the execution is the product of largely autonomous lower order processes. In contrast, an action gist is more detailed, specifying not just an action type but also a particular way of performing the action appropriate to the circumstances. For instance, the soccer player may form a gist in kicking a pass that aims to put the ball into a particular area with a particular weighting that will wrong-foot a defender and allow a teammate to run onto the ball. The action gist directly shapes execution, and when action is sufficiently extended can contribute to the regulation of execution.

Given that *Mesh* employs a different conception of cognitive control to *Autonomous*, a worry might arise that the difference between the two theories is largely terminological. Processes that *Mesh* treats as part of cognitive control count as automatic from the perspective of *Autonomous*. However, such terminological differences are based on substantive conceptual differences and give rise to major differences in empirical prediction. The contrast between *Autonomous* and *Mesh* is especially clear in the case of a skill like golf putting. Here, *Autonomous* sees cognitive control as potentially responsible for initial strategic choices about the type of shot but as playing no role in execution. In contrast, *Mesh* sees cognitive control as contributing directly to execution by way of the influence of situation awareness on the action set and action gist. Note here that the influence of cognitive control on execution is *not* through 'step-by-step' control of the movement—it is through selection of action type, determination of the perceptual-motor configuration, and the parameterization of the action. While there are terminological differences in the way the processes are described, the conceptual differences manifest in a critical difference in prediction. According to *Autonomous* distraction should not impair the execution of the action, and may be beneficial by preventing harmful cognitive interference. According to *Mesh* distraction should tend to hurt execution: poor situation awareness will tend to result in a poorly established action set and/or a mis-specified action gist, resulting in a poor shot.

There are some important qualifications, however. *Mesh* claims that virtually all skilled action depends on situation awareness and an action set, and much action is guided by an action gist. But the relative importance of these cognitive structures increases with the complexity and difficulty of the situation and task. In simple, easy performance conditions there are light demands on situation awareness and the action set, permitting a significant degree of tolerance to distraction and giving the appearance of overall automaticity. But complex, difficult performance conditions impose strong demands on situation awareness and the action set, and because of this performance will be significantly impaired by distraction. We'll argue in Section 4 that these points provide an alternative explanation for experiments purporting to show that the execution of skills like golf putting is automatic.

First, however, we will compare *Mesh* with *Automatic* in more detail. Given that automation is clearly an important part of skill acquisition *Full Cognitive* is implausible, so we won't consider it further. Some may consider *Automatic* to be implausible on the grounds that explicit strategic cognitive processes do appear to play a role in complex temporally extended skills like basketball and figure skating. It remains a vigorously defended position, however (Dreyfus, 2013; Brownstein, 2014), and an evaluation of its strengths and limitations helps to clarify key issues. *Autonomous* shares many key assumptions with *Automatic*, and in Section 4 we'll show that the advantages of *Mesh* in comparison with *Automatic* also apply to *Autonomous*.

3. The Varied Nature of Skill Experience

We now examine *Mesh* and *Automatic* with respect to their ability to explain a set of common forms of skill experience. This strategy requires explanation because many scientists and naturalistically oriented philosophers regard phenomenological evidence as a dubious basis for theory. Firstly, we do not rely on phenomenological evidence as a privileged source of information for skill theory—it is part of a matrix that includes experimental evidence and theoretical reasoning. Secondly, the kinds of skill experience we describe play a pervasive role in intuitions about skill, and are an important source of influence on skill research. Thirdly, the experimental tests used to probe the automaticity (or otherwise) of skill in experimental research can be related directly to some of these forms of skill experience: understanding how these skill experiences are related will provide a conceptual basis for interpreting this research. Fourthly, this analysis of skill experience serves as starting point for a qualitative empirical research program investigating skill performance in natural settings. Laboratory-based experimental research can suffer from problems of ecological validity (Christensen *et al.*, 2015a), so it is important to pursue complementary research streams: experimental research that investigates key questions with high levels of control, and qualitative investigation that illuminates real-world skill performance. The systematic analysis of skill experience we present here helps to emphasize the complex nature of skill and reveals problems that arise from a narrow focus on select aspects of skill.

3.1 Nine Common Forms of Skill Experience

Automatic fits well with some everyday features of personal experience. In particular: (i) attention to performance can be reduced once a skill has been acquired (for later reference we label this *reduced attention*), (ii) a well-learned skill can often be performed in conjunction with other tasks with little detriment (*multi-task tolerance*), (iii) attention to the performance of a highly learned skill can be disruptive (*disruptive attention*), (iv) sense of cognitive effort can be low (*reduced cognitive effort*), and (v) memory for the performance of a highly learned skill can be reduced or absent (*reduced memory*).

It is easy to find instances of each of these phenomena. Experienced drivers who drive cars with a manual gear shift typically don't pay attention to the specific movements involved in changing gear, in contrast with beginner drivers—a simple example of reduced attention. And unlike a novice, under normal conditions an experienced driver can easily have a conversation with a passenger while driving, showing multi-task tolerance. Moreover, if the experienced driver does pay attention to the details of the movements involved in shifting gear this can be disruptive. A novice driver experiences a strong degree of cognitive effort during the performance of many operations, such as reversing out of a driveway, whereas sense of cognitive effort can be low for an experienced driver during the same kinds of maneuvers. A commonly mentioned example of reduced memory is the case of driving a familiar route and having little memory of the drive afterwards. Another example of reduced memory is being unable to remember afterwards whether you locked the front door as you left your house.

However there are also aspects of common experience that are clearly suggestive of a role for cognitive control, and in particular of *Mesh*. These include (vi) enhanced attention to strategic features of a task—the situations, goals, and methods involved in performing the task (*strategic focus*). In the case of driving, not having to pay attention to the mechanics of changing gear allows an experienced driver to devote greater attention to the larger situation, such as proximity to other cars and upcoming tasks like changing lanes. Strategic focus is linked to another common skill experience: (vii) when not enough attention is given to the task at hand the individual can sometimes perform the wrong action, for instance turning as if to drive to work when the goal is to go shopping (an *action slip*). And (viii), although awareness can be relatively low when driving a familiar route it can also be very high in demanding conditions, such as driving at night on a busy highway (*increased attention in response to challenge*). Increased attention can be accompanied by increased sense of cognitive effort (ix), as possibilities are evaluated and decisions made (*increased cognitive effort in response to challenge*).

3.2 *Mesh* versus *Automatic*

When described in an unqualified way these various forms of skill experience seem to conflict: attention and cognitive effort are reduced in skilled action, but also sometimes increased; attention to performance is bad, disrupting automatic processes, but insufficient attention to performance is also bad, resulting in action slips. Some scheme of contextual qualifications is needed to reconcile these contradictions, and we can extract from *Automatic* and *Mesh* different candidate schemes, summarized in Table 1.

The defining claim of *Automatic* is that there is a global reduction of cognitive control in the course of skill learning as automation occurs, with cognitive control making no positive contribution to performance in advanced skill (Figure 1a). Reduced attention, reduced cognitive effort, multi-task tolerance, disruptive attention and reduced memory are all phenomena that can be readily expected to result from this. Reduced attention and cognitive effort can be expected because attention and cognitive effort are associated with cognitive control, which has been supplanted by automation. Multi-task tolerance can be expected because automatic processes can operate in parallel, and because cognitive resources are free if a second task is demanding. Disruptive attention can be expected because attention to automated processes is likely to generate control input that will disturb their normal operation. Reduced memory can be expected because attention is thought to be required for memory formation (Craik *et al.*, 1996).

Strategic focus, action slips, increased attention in response to challenge, and increased cognitive effort in response to challenge are all suggestive of cognitive control, so *Automatic* must locate them outside the range of normal conditions of

	Automatic interpretation		Mesh interpretation	
Skill experience	Scope	Mechanism	Scope	Mechanism
(i) Reduced attention	Advanced skill, normal conditions.	Automation reduces cognitive demand.	Implementation, easy conditions.	Attention focus shifted from automated aspects, low cognitive demand in easy conditions.
(ii) Multi-task tolerance	Advanced skill, normal conditions.	Reduced cognitive demand frees cognitive capacity for othertasks.	Implementation, easy conditions.	Automation of component skills, low cognitive demand in easy conditions.
(iii) Disruptive attention	Advanced skill, normal conditions.	Attention interferes with automated processes.	Implementation.	Misdirected attention to automated aspects of skill control.
(iv) Reduced cognitive effort	Advanced skill, normal conditions.	Automation reduces cognitive demand.	Easy conditions.	Streamlined cognition, low cognitive demand in easy conditions.
(v) Reduced memory	Advanced skill, normal conditions.	Reduced attention results in reduced memory.	Implementation, easy conditions.	Low cognitive demand in easy conditions, shifted attention focus.
(vi) Strategic focus	Pre-expert skill, unusual conditions.	Cognitive demand in unfamiliar conditions.	Primary skill control, challenging conditions.	Shifted attention focus, cognitive demand increases with task difficulty.
(vii) Action slips	Pre-expert skill, unusual conditions.	Insufficient learning.	Especially familiar conditions with low arousal.	Inadequate situation awareness.
(viii) Increased attention in response to challenge	Pre-expert skill, unusual conditions.	Cognitive demand in unfamiliar conditions.	Challenging and unusual conditions.	Cognitive demand increases with task difficulty.
(ix) Increased cognitive effort in response to challenge	Pre-expert skill, unusual conditions.	Cognitive demand in unfamiliar conditions.	Challenging and unusual conditions.	Cognitive demand increases with task difficulty.

Table 1 *Skill phenomena:* Automatic *versus* Mesh

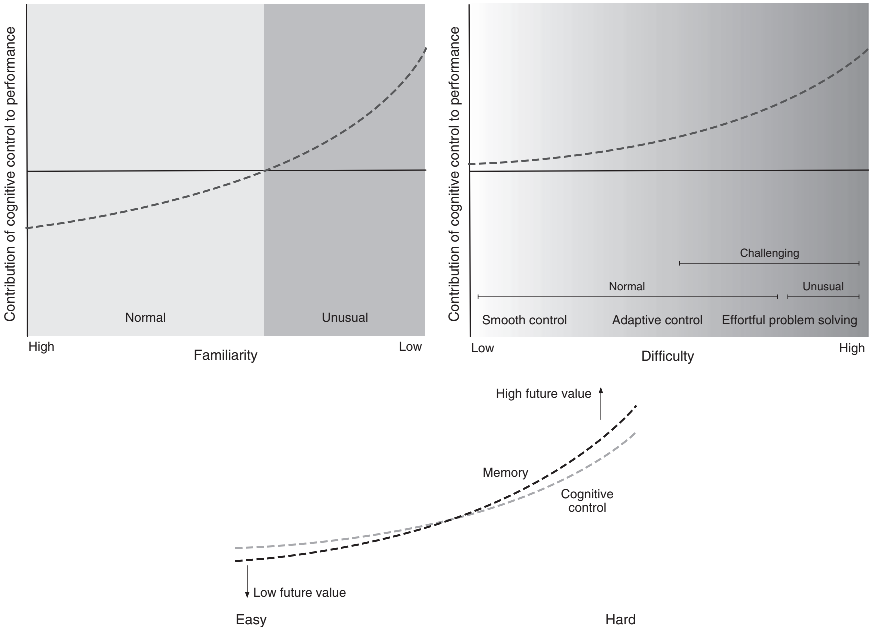

Figure 2 *Cognitive control: familiarity and difficulty.*

competent performance. *Automatic* only sees a positive role for cognitive control in the stages of learning prior to advanced ability (Figure 1a), and in unusual conditions, where responses haven't fully automated (Figure 2a). Reduced memory suggests that attention to performance isn't required, so strategic focus should have no benefit in normal conditions. Indeed, since attention to performance is supposed to be disruptive, attention to the strategic features of performance should disrupt those aspects of control, at least in normal conditions. Action slips are difficult to accommodate within the range of normal skill competency for much the same reason: in normal conditions attention isn't required, so low attention should have no negative consequences. Likewise, increases in attention and cognitive effort in response to challenge should only be beneficial if the challenge lies outside the range of normal performance conditions. Again, attention is supposed to be disruptive in normal conditions (experience iii), so increased attention in challenging-but-normal conditions should have the unfortunate effect of degrading ability just as demand on ability increases. The same is true for cognitive effort.

In contrast, *Mesh* provides an integrated explanation for strategic focus, action slips, and increased attention and cognitive effort in response to challenge. According to *Mesh* cognitive control participates in skilled action and tends to be focused on strategic aspects of task control. We noted above that Bryan and Harter (1899) described a progression in learning telegraphy from focusing on letters, then words,

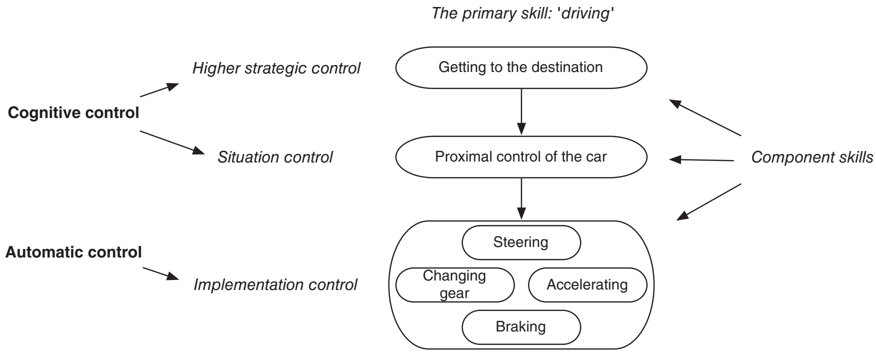

Figure 3 *Control hierarchy: driving.*

then phrases and sentences, and then meaning. This suggests a hierarchical organization to skilled action, with component skills contributing to higher order abilities. Figure 3 illustrates a hierarchical structure of this kind for driving. We'll distinguish between *primary skills,* which are relatively integrated action units, and *component skills,* which are integrated activities that contribute to the performance of primary skills. 'Driving' is a complex primary skill that involves a suite of coupled component skills (including navigating, steering, accelerating and braking, and changing gear).

In Figure 3 the organization of the control of driving is depicted as involving three levels. *Higher strategic control* involves overall control of the primary skill in relation to its goals. In the case of driving this includes navigation to the destination. *Situation control* involves the control of action in relation to the immediate situation. In the case of driving this involves proximal control of the car in relation to features of the situation, including maneuvers like accelerating to traffic speed, maintaining lane position, maintaining a safe distance to other cars, changing lanes, and so on. *Implementation control* involves performing actions that achieve situation control, which in the case of driving includes steering, accelerating, braking, changing gears, and so on.[1]

According to *Mesh* automation tends to be strongest (though not complete) for implementation control, whereas situation control and higher strategic control do not tend to automate strongly (though learning will greatly improve the organization of control). The reason for this is that implementation control involves relatively stable relations (e.g. brake to slow down), while the relation of action to context is usually complex and variable (e.g. brake now to avoid the pedestrian on the crossing). In some cases some of the higher order features of action have a high degree of

[1] Pacherie's (2008) similar hierarchical account of action control has influenced our account. Pacherie places greater emphasis on intentions and forward models. In a companion paper we discuss similarities and differences between the accounts. In a companion paper (Christensen *et al.*, 2015b), we discuss similarities and differences between the accounts.

constancy. For instance, navigation can become automated when a particular kind of journey almost always involves the same route, as in the case of driving to work in the morning. But in general higher order features of action will tend to show substantial variability.

In this account the role of cognitive control in skilled action is to manage the variable features of action, tracking the overall task and the structure of the situation, and adjusting action appropriately. Thus, situation awareness in driving will include awareness of the destination and route, and awareness of the immediate situation, including position on the road, speed, upcoming corners, other cars, and so on. Situation awareness will contribute to an action set, such as a pattern of attention and action appropriate for freeway driving in heavy traffic, or suburban driving at night. It can also contribute to the formation of an action gist, such as gentle early braking when approaching a corner in wet conditions.

Given this, action slips are readily explained as the result of weak higher order control, resulting in misalignment of goals, situation and action. Increased attention in response to challenge can be explained because in challenging conditions higher order aspects of action control tend to be especially complex and variable (consider the routing and traffic problems facing a London cabby). Increased cognitive effort can be explained because in challenging conditions maintaining awareness often requires integrative interpretation, and because action selection is more complex.

Mesh recognizes a mixture of increased and reduced attention so it can also accommodate the five kinds of skill experience we associated with *Automatic.* Enhanced strategic focus is compatible with reduced attention if the reduction of attention is to details of implementation. Thus, a driver can simultaneously have heightened awareness of nearby cars during a passing maneuver and low awareness of changing gears. Enhanced attention and cognitive effort in response to challenge is also compatible with reduced attention and cognitive effort when the conditions are unchallenging. When the strategic features of the task are simple and stable then relatively little information is needed for effective control, and there is little need for interpretation or planning. Reduced cognitive effort is also in part the result of cognitive streamlining, according to *Mesh.* As well as automating implementation, skill learning produces cognitive structures that are well organized for the demands of the task, reducing the cognitive effort needed for effective higher order action control.

Multi-task tolerance can be explained if the conditions are such that relatively little higher order control is needed. Driving on a good road with moderate traffic and clear visibility is undemanding for an experienced driver; she does need to keep track of the relation of the car to the road and other cars, and turn at the appropriate places to reach the destination, but this is simple enough to afford spare cognitive capacity for other activities, such as conversation. Component skills must show some multi-task tolerance because they are characteristically performed in conjunction with other component skills, and indeed, linkage between component skills can reduce cognitive demand. For instance, linkage between clutch control and shifting the gear lever reduces the need directly to attend to either. Disruptive attention can be explained as the misdirection of attention to the details of implementation when its proper focus is on higher order aspects of performance.

Reduced memory is consistent with *Mesh* if the reduction is for details of implementation, or if conditions are easy. Some additional qualification is required here, however, because *Mesh* claims that there is always some cognitive control of action, even in easy conditions (Figure 2b), yet memories for very routine actions can sometimes seem virtually nonexistent. To account for this *Mesh* proposes that memory encoding is affected by more than just attention (Figure 2c). In particular, memory encoding is affected by the relevance of information for future control. Information that is evaluated as likely to be important for future control is preferentially encoded, while information that is not likely to be important in the future is less likely to be encoded, even if this information is operative in immediate control (cf. Anderson and Schooler, 2000; Michaelian, 2011). Broadly speaking, it is more likely that there is something to be learned in challenging conditions compared with easy conditions, and so situational information in challenging conditions is more likely to be relevant in future. But we also think that experts have more fine-grained mechanisms for preferential memory encoding, based on memory structures organized for retrieval demands (Ericsson and Kintsch, 1995; see also Christensen, Sutton, Bicknell and McIlwain, in preparation). If the task demands are such that present information is needed in the future then it is more likely to be encoded, even in easy conditions, while information not relevant to future control may not be encoded, even in challenging conditions.

The combined effect of these mechanisms is that experts will tend to encode large amounts of information *when the information is evaluated as relevant to future control,* but relatively little information when information about the current situation is unlikely to be important in future. Novices are constantly confronted with new tasks and will tend to have rich memories, but have less basis for predicting relevance in general, or relevance to future control. Their memories should therefore incorporate more incidental information than an expert's memories. Overall capacity to remember detail will be less than for an expert because situational information is much more meaningful for the expert. Thus, *Mesh* gives quite different predictions to *Automatic* with respect to memory for performance.

The specificity of the scheme of qualifications given by *Mesh* is important. In general, *Mesh* would not expect reduced memory in challenging conditions (though this is modulated by future relevance), so cases of reduced memory in challenging conditions would be problematic. However the typical examples of reduced memory—like driving a familiar route—are cases where conditions are easy. And conversely, cases that illustrate enhanced attention to challenge—like driving at night on an icy road—are the kind of situations that often produce vivid memories. Multi-task tolerance in challenging conditions would not be consistent with *Mesh*, but again, typical cases of multi-task tolerance involve easy conditions. Thus, it's not hard for a driver to hold a conversation when conditions are easy, but things are different in difficult conditions. Intuitively, conversation is more likely to impair driving ability when driving at night in icy conditions on a winding country road.

Experimental evidence confirms that a secondary task can have a substantial detrimental effect on driving ability (Blanco *et al.*, 2006).

Figure 2b represents the *Mesh* view of increasing cognitive demand as it contrasts with *Automatic* (Figure 2a). The most basic difference is that the x axis in 2b shows difficulty rather than familiarity. *Automatic* effectively assumes that difficulty reduces to familiarity: tasks that are difficult for the novice (and hence cognitively demanding) become easy (and hence cognitively undemanding) with sufficient learning. Cognitive demand arises for the expert only in conditions that are unusual—conditions that haven't been experienced often enough for effective automatic responses to have been acquired. *Mesh,* on the other hand, treats difficulty and familiarity as distinct. While it's true that tasks generally become easier with learning, experts don't perform the same tasks as novices—they move on to tasks that are far more complex and challenging. And some tasks can have sufficient inherent complexity that no amount of learning makes them easy, or easy enough to be fully automated. More specifically, tasks that exhibit *strong control-relevant complexity* tend to be experienced as difficult even with extensive learning, and resist automation. A task has strong control-relevant complexity when (i) there are many task features, (ii) there are strong interdependencies between task features, and (iii) the success of particular actions is strongly sensitive to the specific state of these interdependencies on particular occasions. Accordingly, *Mesh* regards difficulty as the key parameter governing the degree of cognitive involvement in action control, rather than familiarity.

There is a temptation from an *Automatic* perspective to define cognitively involved performance as pre-expert (Figures 1a and 2a). It might accordingly be claimed that putative experts who find their performances challenging (e.g. concert pianists) are for some reason stuck in a pre-expert mode. Given even more training they might attain true expertise. But this is problematic. If individuals who have had a great deal of training and show an advanced level of ability find their performances challenging we should reconsider our theoretical account of expertise, rather than stipulatively define their performance as sub-expert. Perhaps individuals with arbitrarily high capacity and training opportunity would eventually attain automaticity (though see our companion paper), but *Automatic* is not a very interesting position if it describes what skill would be like for gods.

In one respect experts are often dealing with the unfamiliar, since their tasks are complex and frequently involve situations whose fine-grained structure hasn't been previously experienced. But we should nevertheless distinguish between 'normal variability' and unusual performance conditions, where the latter is understood to mean that the general task parameters are different to the typical conditions of performance. A cab driver dealing with the vagaries of traffic in the city is experiencing normal variability, while a car driver attempting to drive a truck for the first time is experiencing unusual conditions.

Figure 2b associates with increasing difficulty three conceptualizations of performance: *smooth control* involves relatively effortless action in easy conditions, *adaptive control* involves greater attention and cognitive effort, while *effortful problem solving*

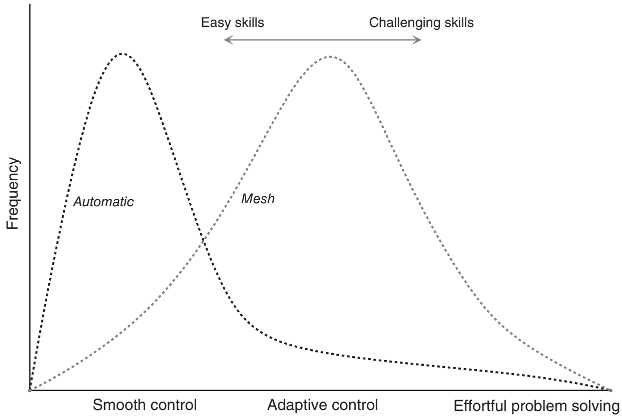

Figure 4 *The distribution of performance conditions.*

involves relatively high degrees of attention and cognitive effort, and temporally extended cognitive processing to determine appropriate action.[2] In our view there is a high degree of continuity: smooth control shades into adaptive control, which shades into effortful problem solving. In terms of these conceptualizations *Automatic* makes two key mistakes: it assumes that smooth control is normal, and it assumes that it involves no cognitive control (compare Figure 2a with 2b, where 'normal' in 2a corresponds to smooth control in 2b). Intuitively, conscious control is associated with effortful problem solving, and we think that the intuitive basis of *Automatic* involves a mistaken interpretation of the phenomenology of smooth control as indicating that control is non-cognitive.

According to *Mesh* normal performance conditions for most skills encompass all three modes of performance. Conditions are noticeably challenging at the high end of adaptive control, and many highly skilled individuals not infrequently need to engage in effortful problem solving. As noted, familiarity doesn't map into difficulty straightforwardly, but performance conditions that are both complex and unusual will be especially difficult. Figure 4 shows more directly the difference in expectations between *Automatic* and *Mesh* with respect to the frequency of the modes of performance that a highly skilled individual experiences. Some kinds of expertise are more challenging than others, and the skew of the distribution differs accordingly. Nevertheless, it is unlikely that many skills have a distribution as skewed as *Automatic* assumes (noting again that even if the distribution were this skewed, smooth control doesn't mean no cognitive control).

[2] These concepts correspond roughly to Dreyfus's Heideggerian conceptions of 'ready-to-hand', 'present-at-hand' and 'unready-to-hand' modes of coping (Dreyfus, 1997). We discuss some of the differences below.

We're treating 'normal' here as a simple matter of frequency, and this is a good first approximation: normal performance conditions are the conditions the individual usually experiences. But in many cases experts are expected to perform well in conditions that they experience relatively infrequently. Statistically speaking, performing in the Olympics is not normal for an Olympic athlete, but it would be odd to describe Olympic performance conditions as *unusual* for an Olympic athlete; they are at any rate not unusual in the way that driving a truck is unusual for a car driver. Similarly, engine failure is not a frequent occurrence for an airline pilot, but coping with an engine failure is expected of airline pilots and part of their normal training (de Crespigny, 2012). To clarify this we distinguish a frequency-based conception of 'normal conditions' from a normative conception of the conditions in which a particular kind of expert is expected to perform well, or the *conditions of expected skill*. What counts as 'normal', broadly understood, will be a complex mix of frequency of actual performance conditions, training, and expectations.

Summarizing, *Mesh* provides a more integrated explanation for the nine kinds of skill experience described above than does *Automatic. Automatic* provides a concise explanation for the first five kinds of experience, but the last four pose difficulties. They are suggestive of cognitive control so *Automatic* must locate them outside the range of normal performance conditions (Figure 2a). This takes no account of difficulty, however, and leads to rather implausible expectations about the kind of performance conditions that are normal (Figure 4). *Mesh* is superficially more complicated, offering a more complicated set of qualifications (Table 1), and making stronger claims about the nature of skilled action (it involves higher order control of assemblages of component skills—Figure 3) and skill domains (they often involve difficulty that can't be fully eliminated with learning). But these claims are well-founded, and they yield a more integrated explanation for the nine kinds of skill experience, and a more integrated picture of skilled performance (Figures 2b and 4).

4. Applying the Framework

Our analysis to this point has distinguished three broad possibilities for theories of skill (*Automatic*, *Full Cognitive,* and *Hybrid*), and two kinds of hybrid theory (*Autonomous* and *Mesh*). We have elaborated our preferred option, *Mesh*, in comparison with *Automatic* by means of a careful comparative evaluation with respect to the ability to explain a set of diverse forms of skill experience. The next step is to apply the framework to extant skill theories. As a starting point we use the framework to illuminate several key types of experimental research and the theoretical interpretations that have been given to the evidence.

4.1 Dreyfus and NDM Research on the Difficulty of Normal Conditions

As noted above, the theory of skill presented by Dreyfus and Dreyfus (1986) is the clearest example of *Automatic*. Dreyfus (1997) places this theory in the context of expertise research conducted within the Naturalistic Decision Making (NDM) framework (Zsambok and Klein, 1997). Like Dreyfus, NDM research has defined itself in contrast with formal decision-theoretic approaches to decision-making, and NDM researchers share with Dreyfus the view that experts don't typically make decisions by generating and analyzing an extended list of options (Klein, 1993). However, NDM research has arrived at a somewhat different picture of expert performance, indicating that experts often engage in quite extensive cognitive processes. For instance, in the context of battle command Serfaty *et al.* (1997) propose a three-stage model of decision-making in which an initial plan is formed on the basis of recognition of the nature of the situation, the plan is then developed by exploring its structure, and is then applied to the situation (pp. 235–8).

To explain this inconsistency between his account of expertise and the findings of NDM research Dreyfus appeals to Heidegger's (1927/1962) tripartite distinction between *ready-to-hand* performance, in which the individual engages in intuitive smooth coping with 'ready-to-hand' equipment, *unready-to-hand* performance, in which conditions are unusual and the individual must act deliberately, and *present-at-hand* performance, where the situation is highly unfamiliar and requires rational deliberation. Dreyfus claims that these are three kinds of skilled response to a situation 'each with its own phenomenology and its own appropriate mode', and that his theory applies to ready-to-hand smooth coping, whereas NDM research has been examining unready-to-hand performance (1997, p. 27). His explanation for why the experts studied by NDM research are exhibiting unready-to-hand performance instead of ready-to-hand performance is that NDM researchers have been investigating 'how decision-making works in complex, uncertain, unstable situations such as emergencies, where experts do not have enough experience to have an immediate, intuitive response' (1997, p. 28). He suggests that this complements the work that he and Stuart Dreyfus have done on transparent intuitive coping.

Several aspects of this attempted reconciliation are problematic. It is a mischaracterization to say that NDM researchers are studying the performance of experts in unusual conditions, as implied by classifying the performance as 'unready-to-hand'. Dreyfus explains unready-to-hand performance by saying that 'when a piece of equipment is missing or when the situation is otherwise abnormal we have to stop and think' (p. 27). But while the experimental conditions that NDM researchers have used are designed to be challenging, they are also intended to emulate real performance conditions. Studying battle commanders, for instance, Serfaty *et al.* say 'we designed an experiment that posed realistic, nontrivial problems, simulated the procedure and materials used in real-world tactical situations, and involved a significant number of military officers' (1997, p. 238). The conditions of performance being studied by NDM researchers are *uncertain,* as Dreyfus recognizes, but they are not *unusual.*

Rather than complementing Dreyfus's theory, NDM research looks like counterevidence. Dreyfus and Dreyfus (1986) described their theory as applying to expertise in domains with *unstructured problems:*

> As we examine in detail how a novice, if he possesses innate ability and has the opportunity to acquire sufficient experience, gradually becomes an expert, we shall focus upon the most common kind of problem area, sometimes called 'unstructured.' *Such areas contain a potentially unlimited number of possibly relevant facts and features, and the ways those elements interrelate and determine other events is unclear*. Management, nursing, economic forecasting, teaching, and all social interactions fall into that very large class (p. 20, emphasis added).

The theory is thus specifically intended to apply to expertise in problem situations that are complex and uncertain (economic forecasting!), and Dreyfus and Dreyfus see this as including many kinds of expertise. Examples they discuss include driving, aviation, nursing, medical diagnosis, air traffic control, chess, and marketing. NDM research defines its scope similarly: as expert decision making in situations where the problems are ill-structured, dynamic and uncertain (Zsambok, 1997, p. 5), and the fields it has investigated overlap with the fields discussed by Dreyfus and Dreyfus (1986) (see the various chapters in Zsambok and Klein, 1997).

Dreyfus and Dreyfus (1986) say that experts deliberate 'when time permits and much is at stake' (p. 40). However this must be relatively exceptional if it's true that experts 'don't make decisions' in normal conditions. Dreyfus and Dreyfus also say that, 'Few if any situations … are seen as being of *exactly* the kind for which prior experience intuitively dictates what move or decision must be made', requiring the expert to evaluate possible actions and/or deliberatively adjust an action to the features of the current situation (p. 37). This is an interesting claim, which anticipates in certain respects the model of Serfaty *et al.* (1997). But it raises for Dreyfus a problem of consistency: if 'few if any' situations are close enough to past experience to be able to rely purely on intuition then experts will *almost always* be using deliberative control. It is impossible to reconcile this with the claim quoted above that experts don't solve problems or make decisions when things are proceeding normally.

Thus, even if some of the claims that Dreyfus has made are broadly consistent with NDM research, they are not consistent with the main claims of his own theory. If Dreyfus is to fully embrace the findings of NDM research he must make major changes to his theory.

Ready-to-hand, unready-to-hand and present-at-hand forms of performance are characterized in terms of a spectrum of familiarity (Figure 5), with ready-to-hand performance occurring in normal conditions (if we take seriously the claim that experts don't make decisions when things are normal). This accords with *Automatic* as depicted in Figure 2a. That ready-to-hand performance should be normal makes sense if the differences between these modes of performance are based on familiarity: increasing familiarity should drive a transition from present-at-hand to ready-to-hand performance. When we frame it in this way it appears that the experts studied by NDM research get stuck partway along the progression, but why? An expert should be very familiar with the problems she deals with as a matter of course

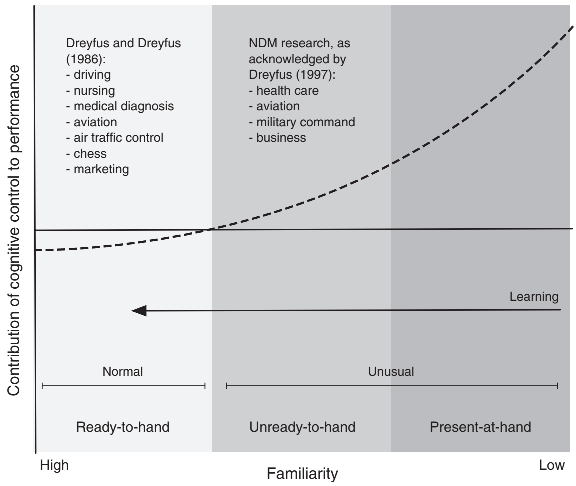

Figure 5 *Dreyfus's account of skill control.*

as part of her expertise. The obvious answer is that the problems are hard: but difficulty isn't taken into account by this conceptualization of performance. Difficult is not the same as unfamiliar.

In the previous section we characterized a spectrum of forms of performance using the concepts 'smooth control', 'adaptive control', and 'effortful problem solving' (Figure 2b). This is inspired by Dreyfus's Heideggerian conceptualization, but there are important differences. Understanding the spectrum in terms of difficulty rather than familiarity is one: whereas Dreyfus describes situations that induce unready-to-hand performance as abnormal, we don't think that a situation has to be abnormal for an expert to be using adaptive control—just mildly difficult. Nor does the situation have to be abnormal for effortful problem solving. Unready-to-hand performance would in our terms be one, relatively strong form of effortful problem solving. We prefer 'smooth control' to 'smooth coping' because 'coping' is too passive a concept. Experts don't simply cope with their environment, they are actively engaged with it. And we think that these forms of performance are highly continuous, whereas in describing them as different modes Dreyfus treats his categories as fairly distinct.

For these reasons Figure 5 and Figure 2b are not directly comparable, though we've designed them to make the comparison as close as possible. As a rough approximation NDM research suggests that for the kinds of expertise investigated the distribution of forms of performance is more like the *Mesh* curve than the *Automatic* curve in Figure 4, skewed in these cases towards effortful problem solving, which is to be expected for challenging forms of expertise. We agree wholeheartedly with the claim that very few situations are so exactly like past experience that a prior solution can be applied without some evaluation or modification.

But taking this claim seriously results in a different theory to that proposed by Dreyfus.

4.2 Tolerance to Distraction in Complex Motor Skills

The forms of expertise investigated by NDM research are ones that many would expect to involve explicit reasoning processes. As we discussed above, it is not uncommon to take the more restricted view that only lower order aspects of performance tend to automate, with higher cognition continuing to play an important strategic role. In Section 2 we distinguished *Automatic* and *Autonomous*, where *Autonomous* holds that the execution of motor skills becomes automated, but that decision-making and other forms of conscious cognition still play a role in complex skills that have a substantial motor component, such as sporting skills like soccer. We further distinguished *Mesh* from *Autonomous* as two forms of Hybrid theory, with *Mesh* proposing that cognitive control makes important contributions to virtually all skills, including those that *Autonomous* regards as largely automatic, such as golf putting. We now examine experimental research that bears on this issue, using the framework we've developed to reveal weaknesses in the framing of the experiments and the interpretation of the results.

Multi-task tolerance is one form of skill experience that is suggestive of automaticity, and some experimental paradigms designed to test automaticity are based on multi-task tolerance. Leavitt (1979) probed the automaticity of puck control in expert ice hockey players by measuring the effect on performance of a distracting second task. Leavitt compared the performances of ice hockey players of varying skill levels in skating through a slalom course while stickhandling a puck. In one condition the subjects performed a secondary task (identifying objects); Leavitt found that the speed and stick handling performance of the experts was minimally affected by the secondary task, whereas the performance of players of lower skill levels was significantly impaired. Gray (2004) used baseball batting as the primary task and a secondary task that involved monitoring tones presented at random times during the batting task. Like Leavitt, Gray found that experts were not impaired by the distracting secondary task (compare Christensen *et al.*, 2015a).

These experiments do not take task difficulty into account, however: in each case the conditions are easy for the experts. The slalom course employed by Leavitt was a straight out and back course with five obstacles—easy compared with game conditions. The *Mesh* prediction is that expert performance would be impaired by a secondary task on a slalom course that players found challenging. Gray's (2004) experiments required baseball experts to hit a virtual ball, where there were only two kinds of pitches (fast and slow). Individuals completed between three and five hundred trials. These conditions are again much easier than the conditions experts would experience during a game, and are also monotonous. *Mesh* predicts that performance would be impaired by the secondary task in conditions that are more realistic and have a degree of challenge commensurate with competition conditions.

4.3 Reduced Memory in Complex Motor Skills

In addition to multi-task tolerance, other forms of evidence are used to infer automaticity. Reduced memory (experience v in Table 1) is also associated with automaticity, and Beilock and Carr (2001) conducted experiments designed to assess reduced memory for performance. They compared novices and experts on a golf putting task in the laboratory. Participants first performed 20 putts from a fixed location on a carpeted floor, attempting to place the ball as close as possible to a cross on the floor 1.5m away. After completing the putts the subjects were asked them to describe the steps involved in a typical putt. This was intended to assess generic knowledge of putting. Subjects then performed a second series of 30 putts, and were again asked to describe the steps involved in a typical putt. In the final phase of the experiment a further 20 putts were performed, and subjects were then asked to describe the last putt they had taken. This was intended to gauge episodic memory for the putt (in contrast with generic knowledge of putting). The results were that, as expected, novices gave shorter generic descriptions than experts (experts have greater knowledge for the domain), whereas novices gave longer episodic descriptions than experts.

In Section 3.2 we argued that reduced memory can be consistent with both *Automatic* and *Mesh,* but that the two theories view the scope of the phenomenon differently. For skills like golf putting *Autonomous* gives the same predictions as *Automatic*: reduced memory should occur in normal (but not unusual) conditions. In contrast, as a first approximation *Mesh* expects reduced memory in easy conditions, but not challenging-but-normal conditions or unusual conditions (Figures 2b and 2c). This, however, is influenced by the specific memory demands of the task. In Beilock and Carr's experiments the conditions for the experts were very easy: the subjects performed 70 identical putts indoors on carpet. The task had no informational dependencies over time, so current information had low relevance for future control once a reasonable standard of performance was obtained. Thus, although these results are consistent with *Autonomous,* they are also consistent with *Mesh.* Putting it another way, Beilock and Carr haven't shown expertise-induced amnesia for expert putting in general, only in easy conditions where information for control has no future relevance.

Beilock *et al.* (2002) conducted a study in which experts did have stronger memories than novices. They compared novices and experts using a 'funny putter': a putter with an S-shape and unusual weighting. Experts using the funny putter had rich episodic memories for putts performed, suggesting high attention and cognitive involvement. This performance situation is clearly unusual, and like *Automatic*, *Autonomous* predicts cognitive control (Figure 2a). But with respect to cognitive demand it may be closer to the challenging conditions an expert golfer must cope with during competition than is performing 70 identical putts on carpet (Figure 2b).

This further shows that our analysis illuminates—and reveals weakness in—extant skill research. Like Dreyfus, Beilock uses a simple distinction between normal and unusual conditions that doesn't recognize the possibility that there might be significant cognitive control in challenging-but-normal conditions. The key question for Beilock and Carr is whether expertise-induced amnesia will be found in challenging-but normal conditions. *Mesh* predicts that expert golfers should show enhanced memory for performance in challenging conditions. There may be reduced memory for some implementation details, but there should be enhanced memory for important aspects of higher order control, such as information involved in adjusting the putt for the specific features of the situation (situation control in Figure 3).

Beilock (2011) suggests that to avoid choking 'The best advice … is to try to play "outside your head" or at least outside your prefrontal cortex' (p. 199). Again, *Mesh* supplies different expectations. On Beilock's account distraction should reduce choking by preventing attention to automatic processes. She says, 'Having a golfer count backward by threes, for example, or even having a golfer sing a song to himself uses up working memory that might otherwise fuel overthinking and a flubbed performance' (2011, p. 77). In contrast, on the basis of *Mesh* we expect that achieving an effective strategic focus will be more beneficial than distraction. Distraction may be helpful in some circumstances, but it will also reduce the quality of the individual's situation awareness and higher order control processes. Methods that improve focus should be especially valuable in challenging conditions, where situation awareness and higher order control is most critical.

In sum, the problems of *Automatic* described in Section 1.3 also apply to *Autonomous* in the case of complex motor skills like golf putting. These problems are evident in Beilock's work: like Dreyfus, she fails to properly recognize the significance of difficulty, and she also fails to consider the possibility that some forms of attention to performance are disruptive and others are not.

5. Taking Stock: Understanding Complex Skills in Challenging Conditions

Mesh places greater emphasis on difficulty and complex action than does either *Automatic* or *Autonomous.* The preceding analysis shows the value of incorporating these aspects of skill into the picture more fully. Everyone knows that some tasks are difficult, and that skilled action can be complex. But giving proper theoretical weight to these features of skill requires integrative theory to address multiple features of skill. The automated aspects of skill are, somewhat ironically, very salient, and it is easy to emphasize them at the expense of other aspects of skill. The positions we've critically examined do just this: they argue for skill automaticity based on select kinds of skill phenomena (experiences i–v in Table 1) without properly considering the kinds of qualifications required or the broader range of phenomena that is relevant. In short, they overgeneralize.

Dreyfus and Dreyfus (1986) clearly expected that expertise in complex skill domains would be substantially automated, even though they noticed in passing what in our view is the basic reason why it isn't (performance conditions are usually too variable). Leavitt (1979) shows multitask tolerance in easy but not realistic conditions. Beilock and Carr (2001) assume that they can generalize from golf putting performance in very easy conditions to putting in general—putting in 'normal conditions'. Beilock *et al.* (2002) examine putting performance in unusual conditions, but Beilock doesn't compare putting in easy, difficult and unusual conditions, which would give a better overall picture of the nature of the control of putting.

In contrast, *Mesh* provides a more nuanced picture (Figure 3b) which accommodates evidence for automaticity while highlighting the need to understand action complexity, demanding performance conditions, and the role of cognitive control. *Mesh* more specifically suggests three core issues that deserve systematic empirical investigation: (i) the range of performance conditions that experts experience, (ii) possible changes in the nature of control across this performance range, and (iii) complex patterns of attention in changing conditions.

With respect to the range of performance conditions experienced by experts, NDM experimental research, designed to be realistic, provides suggestive evidence for the *Mesh* curve in Figure 4. But it would clearly be valuable to examine performance conditions more directly. Our phenomenological analysis can serve as the starting point for systematic qualitative investigation, and an initial step towards this would be validation of the picture summarized in Table 1 with systematic qualitative and cognitive ethnographic research—the investigation of skill experiences in varied real world conditions across a range of skills. The skill experiences of interest for *Mesh* include sense of challenge, sense of cognitive effort, selective focus of attention, action slips, and poor or good memory for performance. Evidence for a range of ordinary and elite skills and performance circumstances would provide a much more detailed empirical basis for evaluating the contrasting theoretical claims depicted in Figure 5.

With respect to changes in the nature of control across the performance range, experimental investigation can give a more detailed picture. Leavitt (1979) and Beilock and Carr (2001) compared novices and experts on tasks at a fixed level of difficulty. One way to probe whether cognitive control in experts varies with difficulty is to titrate the effect of changes in difficulty on measures of cognitive control, such as dual-task interference. Doing this for conditions that range from easy to highly challenging, and for a variety of kinds of skill, would provide a detailed test for the contrasting claims of Figures 3a and 3b. Comparing increases in normal difficulty with changes that make a task progressively more unusual would help to further disambiguate difficulty and familiarity, and might help identify differing patterns of control in challenging-but-normal conditions as compared with unusual conditions.

With respect to complex patterns of attention, the *Mesh* concept of strategic focus has some similarity to claims that we've associated with *Autonomous*, in particular the idea that attention shifts to higher order cognitive processes, such as changes in strategy. Schmidt and Wrisberg make this claim, and Wulf (2007) similarly claims that, 'As individuals gain experience with a certain skill, and the movement becomes more and more automated, the action is assumed to be monitored at progressively higher levels' (2007, p. 147). But according to *Mesh* high order control plays a key role in virtually all skilled action—not just action that involves explicit reasoning. Moreover, as discussed above, we think that awareness can include information about body state and movement, so a shift to awareness at 'higher levels' isn't necessarily a shift away from all lower order detail. Rather, expert awareness should have shifted to focus on the *critical* information for performance; expert awareness will be selective, highly shaped to task demands, and may often 'roam' or 'float' as it flexibly and anticipatively seeks out important information. Attentional control will often include forms of self-regulation, as individuals induce in themselves cognitive, emotional and bodily states appropriate for the situation. We noted in the introduction Kumar Sangakkara's claim that 'in batting, you have to be mindless', but he clarifies this point immediately by noting that being 'a thinking cricketer' is in fact 'about deciding how and when to use your brain; when to think and when not to think' (Sadikot, 2014). This in fact suggests that, rather than being generally mindless, expert cricketers are employing sophisticated forms of attentional control and self-regulation. We also note that, because cognitive control is broader than just conscious reasoning and decision-making, and because many functions of cognitive control are not conscious or only partly conscious, the state that Sangakkara calls 'mindless' may involve significant cognitive control, including strong situation awareness and top-down regulation of the motor system. Investigating these kinds of higher order cognition is challenging because detailed patterns of attention are task specific, vary between individuals, and may be disrupted by attentional instructions that induce 'unnatural' attention patterns. Careful phenomenological investigation is required, together with experiments that are sensitive to the 'natural' attention patterns of experts.

6. Conclusion

Automation has clear benefits for skill control: the integration and simplification of action control can make action production more efficient. But cognitive control nevertheless makes a vital contribution to skill control by determining the nature of the situation and configuring and adjusting lower order sensorimotor processes appropriately. Cognitive and automatic processes thus characteristically operate together in an intimately meshed arrangement, with cognitive control typically focused on strategic task features and automatic control responsible for implementation. Experts often have to perform in complex, difficult conditions, and the interpretive and regulative functions of cognitive control gain increasing importance as difficulty increases.

In developing this account of skill learning and control we've placed a strong emphasis on synthesis, and a sibling paper (in preparation) extends the synthesis presented here to encompass a number of key theories of skill learning and action control. Drawing on these theories we can incorporate into *Mesh* an array of phenomena involved in skill, including proceduralization, dynamical constraints, non-analytic pattern recognition, schematization, efficient memory organization, situation awareness, and action planning. The account also develops further a theoretical explanation for the persistence of cognitive control in advanced skill, and characterizes a transformation in cognitive control to more efficient forms that involve substantial non-linguistic structure. The importance of such synthesis for understanding skill should be emphasized: skill is complex, and, it is difficult to integrate its many facets into a coherent picture. We've argued that a number of influential accounts of skill overemphasize automaticity at the expense of other aspects of skill control.

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