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## The Intelligence of Motor Control

Myrto Mylopoulos

**Abstract:** The *puzzle of skilled action* is that of explaining how it is that it displays robust intelligence despite being largely governed by motor control processes that are often characterized as brute, reflex-like, and paradigmatically unintelligent. In this chapter, I argue that a solution to this puzzle takes the form of an extension to existing *hybrid views of skilled action*, according to which its intelligence is to be accounted for in terms of the combined contributions of intentions and other propositional attitude states, as well as the representations and processes involved in motor control (see, e.g., Fridland 2014, 2017; Christensen et al. 2016; Levy 2017; Shepherd 2017). I further argue that, though such views are on the right track, they sometimes take an overly narrow view of the motor system's intelligence, such that it must be *derived* from intention, rather than inherent in its own operations. I make the case that in order to properly understand the intelligence of the motor system, we must recognize the complexity of the representational structures it utilizes in the control of skilled behaviour, and that this complexity forms the basis for the difference in intelligence between expert and novice performance, and points us towards a solution to the puzzle of skilled action.

Keywords: Skill, Intelligence, Motor Control, Schema Theory

### 0. Introduction

A highly skilled tennis player—let's call her Bianca—intends to return her opponent's serve. Her opponent fires the ball to the side opposite of the one that Bianca occupies. Bianca powers her way towards the ball, and in a lightning sequence, swings her arm back, rotates her shoulder, tightens her grip on her racquet, extends her elbow, swings her arm forward with a precise force, speed, and direction, and makes contact with the ball.

Few would disagree that skilled action like this involves the exercise of a high degree of *intelligence* within a certain domain. In the course of skilled performance, an agent executes the correct actions, at the correct time, and in the correct way. Likewise, many would accept that skill in some domain is acquired by way of extensive practice and training and that, as a result, the bulk of the behaviour involved in skilled action is executed *automatically* and *without thought or explicit intention*.<sup>i</sup> But now consider this: automatic, unthinking behaviours are often assumed to be reflexive and paradigmatically *unintelligent*. They are viewed as lacking the flexibility and sophistication of behaviours that are the product of varieties of thought such as deliberation, problem-solving, and reflection.

These seemingly plausible assumptions together give rise to what I call *the puzzle of skilled action*. The puzzle is this: How is it that skilled action can exhibit such a high degree of intelligence, when so much of it is performed (seemingly) unintelligently and automatically? In this chapter, I'll offer a solution to this puzzle. The solution will take the form of an extension to existing *hybrid views of skilled action*, according to which its intelligence is to be accounted for in terms of the combined contributions of intentions and other propositional attitude states, as well as the representations and processes involved in motor control (see, e.g., Fridland 2014, 2017; Christensen et al. 2016; Levy

2017; Shepherd 2017; Pavese 2019). I argue that, though such views are on the right track, they sometimes take an overly narrow view of the motor system's intelligence, such that it must be *derived* from intention, rather than inherent in its own operations. I further argue that in order to properly understand the intelligence of the motor system, we must recognize the complexity of the representational structures it utilizes in the control of skilled behaviour, and that this complexity forms the basis for the difference in intelligence between expert and novice performance, and points us towards a solution to the puzzle of skilled action.

## 1. Motivating the Hybrid Approach

Not all would agree that the activities of the motor system have any role to play in an explication of the intelligence of skill. In order to see what I take to be the limitations of such an approach, and reasons for preferring a hybrid view that countenances the involvement of motor representations in the intelligence of skill, it will be useful to consider an instance of it defended by Stanley & Krakauer (2013) in a paper titled, "Motor Skill Depends on Knowledge of Facts".

On their view, for an agent  $S$  to have skill at  $\Phi$ -ing,  $S$  must possess propositional knowledge about the activity of  $\Phi$ -ing. In elaborating on what type of propositional knowledge is relevant, Stanley & Krakauer place a special emphasis on knowledge of what to do to initiate an action, claiming that "[k]nowing what to do to initiate an action is clearly factual knowledge; it is the knowledge that activities  $x_1 \dots x_n$  could initiate that action" (4). This type of knowledge is especially important for explaining what they take to be a central feature of skill, namely that its "manifestations [...] are intentional actions" (p.6). Skills are not like reflexes, e.g., withdrawing one's hand from a hot stove; rather, they are such that an agent has direct control over whether and how they are manifested.

Stanley & Krakauer allow that in addition to propositional knowledge, skilled action involves a second component that they refer to as *motor acuity*. They understand this as "... practice-related reductions in movement variability and increases in movement smoothness" (p.8). But according to them, improvements in motor acuity do *not* contribute to the intelligence of skill. This is because they view the kind of learning that results in the sharpening of such acuity to be driven by purely bottom-up, low-level motor mechanisms that are not themselves intelligent. In support of this claim, they point to empirical findings that "healthy subjects will adapt to perturbations like a mirror despite it being contrary to their own intention" (p.8). "Such adaptations," they go on to say, "are not the acquisition of something that characteristically manifests in intentional action, i.e., they are not the acquisition of skill" (ibid).

Stanley & Krakauer are surely right to point out that skills are intentional actions, so any ability that manifests in skill must also be one that manifests in intentional action. But why deny that the adaptations involved in improvements of motor acuity are not themselves intentional? The key move here is the claim that they are "contrary" to the agent's intention. And since, on a standard view of intentional action, an action is intentional only if it is suitably caused by an agent's intention, activity that is causally independent of such a state does not thereby qualify.

Reflected in their claim that motor acuity proceeds independently of intention, is a view on which the motor system is *modular* and informationally encapsulated, at least to an important extent. A system is informationally encapsulated to the degree that it lacks access to information stored outside of it in the course of processing its inputs (Fodor 1983). When a system is informationally encapsulated with respect to the states of the central system—those states familiar as propositional attitude states—this is referred to as *cognitive impenetrability* or *cognitive impermeability*. Pylyshyn (1999) provides a fairly standard characterization of this notion, according to which, "... if a system is cognitively penetrable then the function it computes is sensitive, in a semantically coherent way, to

the organism's goals and beliefs, that is, it can be altered in a way that bears some logical relation to what the person knows." (p.343) For instance, in the famous Müller-Lyer illusion, the visual system fails to be sensitive to the content of the belief that the two lines are identical in length, so it is cognitively impermeable relative to that belief

Is it true that the motor system is cognitively impermeable in this way relative to an agent's intentions? First off, it is clear that there must be *some* degree of permeability, since otherwise no intentional action would ever be successfully performed. Still, the degree to which the motor system is sensitive to the content of intention might be limited in a way that prevents us from ascribing to it a role in underpinning the intelligence of skill. Stanley and Krakauer seem to think so on the basis of experimental work employing visuomotor rotation tasks. In such tasks, the participant is instructed to reach for a target on a computer screen. They do not see their hand, but they receive visual feedback from a cursor that represents the trajectory of their reaching movement. On some trials, the visual feedback is rotated relative to the actual trajectory of their (unseen) hand during the reaching task. This manipulation allows experimenters to determine how the motor system will compensate for the conflict between the visual feedback that is expected on the basis of the motor signals it is executing, and the visual feedback it actually receives. The main finding is that the participants' reaching movements "drift" in the direction *opposite* the rotation. So, for example, if the rotation is 45 degrees clockwise, participants' movements will show drift 45 degrees *counterclockwise*. This is thought to be the result of an implicit learning strategy that the motor system adopts in order to reduce the conflict between expected and actual sensory feedback from the reaching movement it programs.

For their claim that motor adaptation—which they view as an aspect of motor acuity—does not constitute intentional action, Stanley & Krakauer (p.8) focus on a variant of this paradigm devised by Mazzoni & Krakauer (2006), wherein participants are instructed to adopt an explicit "cheating" strategy—that is, to form intentions—to counter the perturbation. This is achieved by placing facilitating targets at 45 degree angles from the proper target (Tp), such that if participants aim to hit those neighbouring targets (Tn), the cursor will hit the Tp, thus satisfying the primary task goal. Initially, reaching errors related to the Tp are almost completely eliminated. The cursor hits the Tp as a result of the explicit strategy to hit the Tn. But as participants continue with further trials, their movements *once again* start to drift towards the Tn and *away* from the Tp, despite their intention to hit it. Stanley & Krakauer (2013) take this to be evidence that motor acuity can develop contrary to an agent's intentions, and thus does not manifest in intentional action.

Is this correct? I think some care is needed in interpreting the results. The important thing to note is that there are *two* task goals in this context, *both* of which have corresponding intentions. There is the primary task goal of hitting the Tp and the secondary task goal of hitting the Tn in order to hit the Tp. Likewise, there is the primary intention to hit the Tn, and a secondary intention, the satisfaction of which serves as a means to the satisfaction of the primary one. Importantly, in order to satisfy the secondary intention, it is not enough that the agent merely intend to *aim* for the Tn. The trajectory of the cursor is determined by the actual trajectory of their arm. The participant must thereby intend to *hit or reach for* the Tn. What's more, this is the most proximal intention of the agent, i.e., the intention that directly initiates and guides the relevant action, and not the one that corresponds to the primary task goal of hitting the primary target.

The upshot here is that, though Stanley & Krakauer are correct that the kind of motor adaptation exhibited in the task occurs independently of *some* intention that the agent possesses, i.e., the primary intention to hit the Tp, it does not occur independently of *all* intentions, i.e., the secondary intention to hit the Tn. And this consideration is enough, I think, to undermine their denial that motor acuity manifests in intentional action. Motor acuity is indeed driven by an agent's intention—the most proximal one they have formed—though it is not always sensitive to or

cognitively permeable by all of an agent's intentions, including the ones that those proximal intentions serve.

A more general worry for the type of approach that Stanley & Krakauer defend is that it would seem that what a skilled agent gains as they progress from novice to expert in  $\Phi$ -ing, and the intelligence of their performances increases in some domain, is primarily knowledge what to do to initiate a wide variety of actions relevant to that domain. But this does not seem sufficient to account for the difference between a novice and expert's skilled behaviour. Both may know how to initiate some action or set of actions, but it is the expert's *implementation* of these actions after initiation that sets them apart from the novice—and in particular the *way* that they guide their movements. Granted, we are told by Stanley & Krakauer that “[t]he same kind of knowledge that is used to initiate an activity can also be injected at any time in the ongoing course of that activity. For example, a tennis player changes her mind and switches from a groundstroke to a drop shot based on the position of the opponent” (p.5). But once again this tells us nothing about the way the expert guides her drop shot to completion. An appeal to motor acuity will not even help here, since it can only illuminate differences in movement variability and smoothness, but not differences in the implementation of the action itself, having to do with its functional and temporal organization. At best, then, the type of account defended by Stanley & Krakauer (2013) seems incomplete when it comes to explaining the difference between the kind of intelligent guidance that an expert deploys and that which a novice does. For this, we must look downstream of action initiation at the psychological processes that implement the movement.

Before moving on, it is important to acknowledge a view that is more nuanced than that of Stanley & Krakauer (2013) with respect to the role that propositional knowledge might play in skill, and indeed *links* an agent's propositional knowledge pertaining to a certain skill to the motor representations that they deploy in the service of said skill. This is the view defended by Pavese (2019), according to which skill requires knowledge of a proposition *under a practical mode of presentation*, and on which such modes of presentation are, in turn, to be understood in terms of motor representations. Pavese argues that the motor representations available to an individual agent for performing a certain task do not just represent those tasks or the action outcomes that are associated with them, but rather the *method* by way of which they are to be performed in accordance with the agent's practical abilities. Think of the different *ways* in which one might perform the task of kicking a ball, for example, in terms of the exact path one's leg takes and the exact angular arrangements of the different joints involved. These all correspond to the different methods that one can deploy in order to kick the ball. On Pavese's account, these methods, in turn, constitute the practical mode of presentation under which the propositions underlying skill are known. So on this view, “knowing a proposition about, say, how to grab a bottle using a motor representation of that task is just one way of knowing a proposition under a practical mode of presentation” (p.804).

While I am highly sympathetic to Pavese's (2019) careful account of motor representations as a type of practical representation—indeed, it is consistent with what I go on to say in this chapter—the main difference between our views is that I do not commit myself to the claim that the type of knowledge one possesses in skill that is secured by one's possession of the ability to deploy relevant motor representations is best understood as knowledge of a proposition under a practical mode of presentation. There may be other reasons to hold that knowledge of a proposition is required for skill (see, for instance, those discussed by Pavese 2018 pertaining to a belief requirement on intentional action), but I do not commit myself to holding that the acceptance of those reasons entails that the role of motor representations in the possession of a skill must also be understood in terms of propositional knowledge.

Regardless of this particular point of disagreement, given that Pavese's view countenances a role for both propositional attitude states and motor representations in the intelligence of skill, I take

it to be an instance of the type of hybrid view of skill that I endorse. In short, hybrid accounts are not incompatible with a role for propositional knowledge in skill, so long as there is also a role for motor representations.

In what follows I want to make a case for an additional dimension of the intelligence of motor control that sometimes gets overlooked in hybrid accounts. On *one way* of understanding the intelligence of motor control, it *derives* from its sensitivity to the content of intention or other propositional attitude states, so that it may be viewed as a form of “trickle down” intelligence. As an articulation of this view, consider Fridland’s (2017b) claim that “... some automatic processes are not unintelligent *since they bear robust, systematic relationships to personal-level intentional contents* (p.4339, emphasis mine; but cf. Fridland 2013 p.884, Fridland 2017a). If this is correct, then it is solely in virtue of being sensitive to personal-level intentional contents that the motor system is intelligent. But I think we can say more than this. In particular, I will argue that the intelligence of the motor system goes beyond that which is derived from intention, or other personal-level states. Once we properly understand the types of representation that the motor system employs to perform its tasks, we can better see that the motor system is intelligent in its own right.

## 2. Intelligence as flexibility

First, let me briefly say more about the notion of ‘intelligence’ at work here. Along with others (see, e.g., Levy 2017, Shepherd 2017, and Fridland 2014, 2017), I suggest that a central feature of intelligent behaviour is its *flexibility*. This seems to capture our commonsense ways of thinking about intelligent action. When one thinks of a paradigmatically *unintelligent* response, one often thinks of a reflex. Reflexes are rigid stimulus-response pairings with a highly limited range of available mappings from stimulus to response. Intelligent behaviour, on the other hand, is sensitive to a wide range of information, both external to the agent and internal to its psychology. This is especially apparent in the case of skilled action. As Fridland (2014) has persuasively argued, at the heart of skilled action control is “an agent’s ability to guide and modify her actions appropriately” (p.2732), such that the processes underlying such control are “flexible, manipulable, subject to learning and improvement, responsive to intentional contents at the personal-level, and holistically integrated with both cognitive and motor states” (ibid). So if we want to account for the intelligence of motor control in skill, we must account for its flexibility. No doubt some of this flexibility will come from its top-down sensitivity to the content of an agent’s intentions. But as Levy (2017) correctly to my mind points out, motor mechanisms also flexibly adapt to ongoing changes in the environment in a way that does not conform to a pattern of brute reflexes. By way of illustration, he asks us to consider the motor representations of a skilled jazz pianist:

She may respond to a broad variety of cues *online*, that is, without requiring (or having time for) top-down deliberation. An improvising pianist may respond to subtle cues from the bass player, to changes in the ambiance of the room and the expectations of the audience, to feedback from her instrument and the proximity to the next break in the performance. Famously, her exquisite sensitivity to a broad range of cues may extend to some cues of which she lacks personal-level awareness. Jazz musicians, for instance, regularly report that they are surprised by their own playing, indicating a lack of personal level awareness of information to which they respond. The kind of flexibility and ongoing responsiveness to variations in the conditions under which the action unfolds is the mark of skill (Fridland 2014) but *it is the motor mechanisms that intelligently adjust to these variations.*”

(p.520, emphasis mine)

According to Levy, the motor system is thus intelligent since "[t]he genuine mark of intelligence [...] is the capacity to flexibly adapt in an appropriate manner to environmental perturbations. It is this kind of flexibility that distinguishes the intelligent mechanism—or agent—from the unintelligent" (p.518).

I think Levy gets this point exactly right. Even if the pianist has certain general intentions to "read the room" or to "go with the flow" of the performance, the subtle variations that their playing exhibits in response to the environment are not primarily guided by such intentions, but by downstream representations of the motor system. But in order to see how this might be, we need a more robust understanding of just what these representations are like.<sup>ii</sup> Once we have this, we can see that motor acuity involves more than simple reductions in movement variability and smoothness, but also the fine-tuning of an action in terms of its functional and temporal organization. To see this, it will be useful to start by highlighting two main features of motor representations.

First, there are good reasons to think that they are not propositionally-formatted. Elisabeth Pacherie and I have argued for this conclusion elsewhere (Mylopoulos & Pacherie 2017, p.321-323). The propositional format of beliefs, desires, and intentions, underlies the types of inferential transitions and rationality constraints that are characteristic of practical reasoning. Given an agent's desire that some state of affairs obtain, and their belief that performing some action A will result in that state of affairs, it is rational for them to form the intention (here the conclusion of practical reasoning) to A. Moreover, it is irrational for them to form the intention to B, if they believe that B-ing is not compatible with A-ing. But we plainly do not ascribe irrationality to an agent who makes an error in action execution, say failing to accurately reach for some target. The constraints governing the motor system are not the norms of rationality. Rather its computations are governed by biomechanical constraints and learning mechanisms that aim to reduce sensory feedback error. And there is good reason for this. As Butterfill & Sinigaglia (2014) point out, "[t]he many requirements on motor planning cannot normally be met by explicit practical reasoning, especially given the rapid and fluid transitions involved in many action sequences. Rather they require motor processes and representations" (123).

Second, motor representations are not limited to specifying the detailed kinematic features of bodily movement, such as force, direction, and speed. Rather, they also seem capable of specifying what some have called "action outcomes" (Butterfill & Sinigaglia 2014), that is, action types that might vary in their specific kinematic features while still preserving the same functional organization.

In the next section, I fill in this picture by appeal to an influential theory in the motor control literature. I argue that a proper understanding of the nature of motor representations offers us a clearer account of the ways in which it implements the flexibility required of it for intelligent action.

#### **4. Two Types of Motor Representation: Motor Programs and Motor Commands**

The key to understanding the intelligence of the motor system, and of skilled action more generally, lies in recognizing that motor control involves rich representational control structures that are intermediate between intention and behaviour (Schmidt 1975, 2003; Arbib 2003; Jeannerod 1997; Mylopoulos & Pacherie 2016). This intermediate level of representation contributes to the sensitivity and thereby flexibility and intelligence of motor control in ways that outstrip the contribution of intention.

On my view, motor representations are the psychological states that mediate between intention and behaviour, and encode the goals specified in an agent's intention and the means to those goals in a motoric format. By appeal to an influential theory within the cognitive psychology of motor control known as *schema theory* (Schmidt 1975), we can further develop this line by introducing two different types of motor representation that are hierarchically related. These are (i) *motor programs*, which specify the general form of an action type, and (ii) *motor commands* computed on the basis of motor programs, which specify the detailed kinematics of the action given the condition of the agent (e.g., current bodily position) and the present context (e.g., distance from target objects).

Importantly, and as others have done (e.g., Pavese 2017) it is useful to divide into two phases the computation between the input of the proximal intention and the output of corresponding behaviour. In the first phase of computation, the motor system takes as input the proximal intention to  $\Phi$ , and outputs a motor program that corresponds to  $\Phi$ -ing. In the second phase, the motor program is taken as input, and the details of the motor program are computed, yielding the output of motor commands that specify the fine-grained aspects of the movement, such as its force, direction, and velocity. In order to better understand this process, we must better understand the nature of motor programs and motor commands respectively.

I start with the notion of a motor program, as described by schema theory. According to schema theory, a motor program is a stored representation in LTM of the invariant features of an action type. The invariant features of an action type are those that remain the same—or with negligible differences—across several token performances of it. There is much ongoing debate as to which precise features are invariant, but two proposed features are (i) an action's relative timing, and (ii) its functional organization. The relative timing of an action refers to the set of ratios that define the temporal structure of the action. Each of these ratios is calculated by taking the duration of some part of the action and dividing it by the total duration of the action sequence as a whole. Thus, we can “stretch out” and “compress” various action types (e.g., extending one's elbow, raising one's arm), by increasing or decreasing the total duration of the movement, while keeping the ratios fixed. Next, functional organization refers to the spatial configuration and temporal ordering of the movements that define the functional structure of the action. For instance, a reaching-and-grasping movement typically has the following functional organization: elevation of the acting limb, extension of the elbow, and forward movement towards the target. Together, the relative timing and functional organization of an action serve as “blueprints” for that action type.

In addition to invariant features, action types also have what are known as *surface features*, which are those that change across token performances. The surface features are represented in the motor program by open parameters, the values of which are assigned through a process of *parameterization*, in accordance with the situation of action and feedback during execution. This parameterization thus plays the role of “scaling” the action to the present context. For example, while the action of throwing an object has invariant features invoking specific shoulder and elbow mechanics, it also has surface parameters corresponding to, e.g., which limb to use, what object to throw, how fast and far to throw it, and in what direction to throw it (Schmidt and Lee 2014). Once the parameter values have been selected, the specific movement can be executed in a way that is tailored to the situation of action. This explains why, each time we perform some action, we do not perform it in the exact same ways we have before, nor do we perform it in an entirely novel way. Motor programs allow for the storage of a stable representational structure corresponding to a general action type, as well as the scaling of the action to the present context.

Within this framework, motor learning is understood both as a process by which the general form of a motor program is acquired, as well as a process by which parameterization of a given motor program is fine-tuned. There is evidence that these two aspects of the learning process can be

differentially affected by learning conditions. For instance, using randomized learning trials (vs. blocked learning trials) facilitates the learning of the motor program, but degrades the learning of parameterization. The explanation for this is that randomized learning prevents the agent from responding in the same way from trial-to-trial, requiring them to reconstruct the motor program “from scratch” each time. At the same time, reducing how much feedback the agent receives during practice also facilitates the learning of the motor program, but degrades the learning of parameterization. This is because no sensory feedback is available in order to determine whether parameterization was successful on that trial (Schmidt 2003).

In order to explain how motor programs for action types are acquired and fine-tuned, schema theorists posit two types of *schema* that are stored in LTM and developed across a lifetime of practice and experience. The so-called *recall schema* stores mappings between parameter values (e.g., force and speed) of a general motor program and specific action outcomes resulting from executing that program with those parameters (e.g., distance thrown) given the present context. The recall schema contributes heavily to the process of parameterization. The so-called *recognition schema* stores mappings between past action outcomes generated by executing the motor program (e.g., distance thrown), and the outcome of executing the program (e.g., distance thrown).

We can further introduce a distinction between basic and complex motor programs corresponding to basic and complex action types. Basic action types (e.g., bending of knees, swinging of arm, straightening of elbow) are those that the agent can perform without doing something else first.<sup>iii</sup> Complex action types (e.g., jump shot, tennis serve, volleyball spike, cartwheel) are constituted by a structured set of functionally and temporally organized basic action types. Basic motor programs correspond to basic action types, while complex motor programs correspond to complex action types. So, for example, the complex motor program for a cartwheel might be constituted by a set of basic motor programs corresponding to the preparatory phase, movement phase, and follow-through phase. The preparatory phase might include basic motor programs for planting the dominant foot, and raising one’s arms above one’s head. The movement phase might include basic motor programs for the rotation of each arm and bending of the torso. And the follow-through phase might include basic motor programs for the flexing of the shoulders, and tightening of the abdominal muscles. In executing this complex motor program, each of these basic motor programs would be parameterized given the present condition of the agent, the context of action, and past learning experience.

I take the framework provided by schema theory to be a highly promising candidate for understanding the nature of the motor representations and structures that mediate between intention and action. Taking this framework on board, we can revisit our previous question of what accounts for the difference in skill and intelligence between the novice and the expert performer. A credible answer now presents itself: differences in the intelligence of performances by novices and experts are marked by differences in flexibility. And differences in flexibility are supported by differences in the complexity, organizational structure, and fine-tuning of an agent’s motor programs underlying skilled behaviour.

Indeed, we have empirical evidence that this is a central difference between experts and novices. The evidence derives from the application of a method known as the *structural dimensional analysis of mental representation* (SDA-M). The aim of this method is to map “mental representations as integrated networks of [basic action concepts] across both individuals and groups, by providing information on relational structures in a given set of concepts with respect to goal-oriented actions” (Schack et al. 2014, p.2).

The first step of this method is to select a complex action type (e.g., tennis serve) and then, with the help of experts, coaches, and non-experts, break it down into basic action types and determine their correct functional and temporal sequencing. Next, participants are grouped into

novices and experts, and presented with an “anchor” basic action concept corresponding to a basic action type (e.g., bending of the knees). They are asked to perform a series of pairwise comparisons between that concept and the basic action concepts corresponding to all the other basic action types in the set. Participants must judge whether the given basic action concept is functionally related to the anchor concept in movement execution. They perform this task until all basic action concepts in the set have been compared to all other basic action concepts in the set, and a distance scaling is available between each one. A hierarchical cluster analysis then structures the set of basic action concepts into a hierarchy, and a factor analysis is performed to reveal the dimensions in the hierarchy. Finally, the degree of invariance in judgements within each group of experts and novices, as well as between the groups, is determined. The result of this procedure is a “dendrogram”, which is thought to depict the structure of motor programs stored in LTM that corresponds to a complex action type for novices and experts respectively.

In a recent study, this method was applied in a structural analysis of the motor representations underlying the tennis serve for novices and experts (see Fig 1 from Schack et al. 2014). There were three main findings when it came to the dendograms of experts. First, they were organized in hierarchical tree-like structures. Second, they had a high degree of similarity across individuals. Third, there were no significant differences between the structure depicted in the dendograms of the experts and that of the predetermined functional and temporal sequencing of the tennis serve. For novices, however, the dendograms displayed less hierarchical structure, a higher degree of variance across individuals, and were more poorly matched with the functional and temporal organization of the tennis serve.

The picture that emerges from these studies is that the motor system has a complex store of information that is derived from practice and experience, and that it is this resource that allows for the kind of sophisticated flexibility that we see in the case of skilled action, and that thereby accounts for a significant portion of its intelligence, in a way that goes beyond the contributions of an agent’s intentions.

## 5. Conclusion

To take stock, I’ve presented a view on which we cannot account for the intelligence of skilled action without taking as central—as other hybrid views do—the coordination between an agent’s intentions and their motor system. Importantly, I’ve further argued that the intelligence of the motor system is not exhaustively derived from that of intention, but rather resides in its access to rich representational structures that are built up from experience and training. In proposing this view, I agree with other hybrid theorists that motor control is “intelligent all the way down” (Fridland 2017). What I hope to have done is offered a credible way of illuminating an important aspect of just what this means.

### Note

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<sup>i</sup> This is supported by two popular considerations. First, there is what Montero (2016) calls the *just-do-it principle*: the widely appealed to idea that experts perform best when they’re not thinking about or focused on what they are doing. Second, there are real-time constraints on skilled action that prevent experts from thinking about what to do next. For instance, cricket batsmen must select a shot based on the trajectory of a ball which may travel at up to 160 km per

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hour (Yarrow, Brown, & Krakauer 2009). Similarly, elite chess players can play at a rate of 5 to 10 seconds per move (Dreyfus 2002, p.372).

<sup>ii</sup>I do not here make a case for thinking that the motor system carries out its computations by way of representations in the first place. For convincing support, see Pavese (2017) and Butterfill & Sinigaglia (2014).

<sup>iii</sup> I take the notion of a basic action type appealed to here to be synonymous with Pavese's (2017, 2019) notion of *elementary operations*.

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