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Skill and motor control: intelligence all the way down

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Abstract When reflecting on the nature of skilled action, it is easy to fall into familiar dichotomies such that one construes the flexibility and intelligence of skill at the level of intentional states while characterizing the automatic motor processes that constitute motor skill execution as learned but fixed, invariant, bottom-up, brute-causal responses. In this essay, I will argue that this picture of skilled, automatic, motor processes is overly simplistic. Specifically, I will argue that an adequate account of the learned motor routines that constitute embodied skills cannot be given in a purely bottom-up, brute-causal fashion. Rather, motor control is intelligent all the way down. To establish this, I will first review two recent accounts of skill, Stanley and Krakauer (Front Hum Neurosci, 2013. doi:10.3389/fnhum.2013.0050) and Papineau (R Inst Philos Suppl 73:175–196, 2013), which characterize the automatic motor control responsible for the fine-grained movements constitutive of motor skill as brute, low-level phenomena. I will then isolate five key features that should apply to skilled motor control, if these accounts are correct. Together, the accounts posit that motor control is: (1) ballistic, (2) invariant, (3) independent of general action trajectories, (4) Insensitive to semantic content, and (5) independent of personal-level intentions. In the final section of this paper, I will appeal to optimal control theory for empirical evidence to challenge the commitment to skilled action as qualified by the above features.

Keywords Motor control · Know how · Skill · Optimal control theory

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When reflecting on the nature of skilled bodily action, it is easy to fall into familiar dichotomies such that one construes the flexibility and intelligence of skill[1] at the level of intentional states while characterizing the automatic motor processes that constitute motor skill execution as learned but fixed, invariant, bottom-up, brute-causal responses. In this essay, I will argue that this picture of skilled, automatic, bodily action is overly simplistic. Specifically, I will argue that an adequate account of the learned motor routines that constitute embodied skills cannot be given in a purely bottom-up, brute-causal fashion. Rather, the motor control involved in skilled action is intelligent all the way down.

To establish this, I will first review two recent accounts of skill, Stanley and Krakauer (2013) and Papineau (2013), which characterize the automatic motor control responsible for the fine-grained movements constitutive of motor skill as brute, low-level phenomena. I will then isolate five key features that should apply to skilled motor control, if these accounts are correct. Together, the accounts posit that motor control is: (1) ballistic, (2) invariant, (3) independent of general action trajectories, (4) insensitive to semantic content, and (5) independent of personal-level intentions. In the final section of this paper, I will appeal to optimal control theory for empirical evidence to challenge the commitment to skilled action as qualified by the above features.

1 Skill: cognitive thought plus motor reflex

Though contemporary philosophical accounts of motor skill are rare, in those that have been forwarded recently it is easy to isolate a clear trend. The trend is to construe motor skill as a hybrid phenomenon composed of a cognitive component and a motor component. The cognitive component is usually cashed out in terms of propositional knowledge or intentional states and the motor component is construed in terms of automatic, low-level, causal processes, which are acquired through brute repetition.[2] A hybrid account of skill is offered by Stanley and Krakauer (2013; from hereon S&K) and Papineau (2013).[3]

1.1 Stanley and Krakauer on skill

On the S&K view, motor skills are composed of two components: propositional knowledge and what they call, following Shmuelof et al. (2012), "motor acuity". For S&K, "manifesting any kind of knowledge, and any kind of skill, requires possession of both [perceptual and motor acuity and propositional knowledge]" (p.

[1] In the course of this paper, when I use the word "skill" I will be referring exclusively to skilled bodily actions. I will not take a stance on whether any subpersonal processes, whether perceptual or motor, are properly classified as skills and though I think that a theory of bodily skill will have various interesting implications for our understanding of cognitive skill, I will remain silent on those implications here.

[2] For a notable exception, see Levy (forthcoming) where he forwards a hybrid account where intelligence characterizes both personal-level intentional states and motor representations.

[3] Such an account is also gestured at by Wu (2013).

16). In line with the Intellectualist account presented in Stanley and Williamson (2001) and Stanley (2011a, b), the propositional knowledge that a skilled agent possesses is entirely responsible for the intelligence or cognition involved in skill. That is, the Intellectualist is not committed to the idea that only propositional knowledge contributes to skillful activity but he is committed to the fact that no other aspect of skill will require explanation in cognitive, epistemic, semantic, or conceptual terms.

According to Stanley's Intellectualist account of know how, if an individual has a skill,[4] what that person knows is a proposition no different from the proposition that she might know when she *knows that*, *knows who*, *knows where*, *knows what*, or *knows why*. So, if Hannah knows how to ride a bike, that is, if she has the skill of bike riding, then what Hannah really knows is the answer to the question, "what is the way for you to ride a bike?" That is, in a particular context *c,* we can say that Hannah knows how to ride a bicycle, "if and only if there is some contextually relevant way *w* such that Hannah stands in the knowledge relation to the Russellian proposition that *w* is a way for Hannah to ride a bicycle and Hannah represents *w* under a practical mode of presentation'' (Stanley and Williamson 2001, p. 430). In short, *S* knows that *w* is the way to φ, where the way to φ is represented as a Russellian proposition, and *S* considers that *w* is the way to φ under a practical mode of presentation. According to the Intellectualist, knowing that *w* is a way to φ is constitutive of know how or the cognitive aspect of skillful action.

It's important to note that there remains an open question about how finely or coarsely to individuate the proposition that Hannah knows and, hence, to what extent that proposition can account for the particular detailed movements manifest in Hannah's bike riding on a particular occasion.[5] In Stanley (2011b), it appears that propositions ought to be individuated somewhat finely such that individuals who possess different levels of skill will know different propositions. As such, if Mira knows how to dunk a basketball better than Rohan, then Mira and Rohan do not know the same proposition. Likewise, as Stanley explains, when we say that John plays Chopin better than Mary, "[w]e are comparing the way in which John knows how to play Chopin to the way in which Mary knows how to play Chopin, and declaring the first superior to the second" (2011b, p. 50).

Nonetheless, on Stanley's account, the proposition that an individual knows will not be individuated so finely that it will be able account for the specific detailed movements involved in performing an action in a particular situation, at a particular time, in response to specific situational cues, etc.[6] Presumably, these detailed movements make a significant contribution to both the success and expertise of a

[4] For Stanley, knowing how is equivalent to having a skill.

[5] See Fridland (2013) for a discussion of problems associated with individuating propositions either in a coarse or fine-grained way.

[6] It is possible to cash out propositions in a more fine-grained fashion such that every variation in movement execution is mirrored by an improvement in propositional knowledge. This is the view forwarded by Pavese (2013). However, on the S&K view, the fine-grained, kinematic details of motor skill execution are *not* cashed out in terms of propositional knowledge but rather in terms of motor acuity.

skill[7] but, on Stanley's view, they are accounted for not in terms of the propositions that a skilled agent knows but in terms of motor acuity. This interpretation of the Intellectualist account is justified since, as I've argued previously (2014):

> [N]either Stanley and Williamson (2001), Stanley (2011a, b) nor S&K give any indication of how it is that propositional knowledge could be responsible for the fine-grained, detailed motor control that is developed through practice and training and expressed in the execution of skilled actions. S&K spend a lot of time discussing the propositions required for acting intentionally, but they do not even gesture towards an explanation of how knowing various propositions will govern the execution or implementation of those propositions in a nuanced, detailed, particular, controlled way.
>
> Both because they ignore an account of how control could be guided by knowledge of propositions, and because they focus on the role of motor acuity in accounting for the fine-grained movements of motor skill, it seems reasonable to attribute to S&K the view that control is simply a matter of motor acuity. That is, since it is only in reference to motor acuity that any mention of fine-grained control is made, I can only assume that it is motor acuity that is supposed to account for the particular, detailed, nuanced, fine-grained control manifest in motor skills (p. 2739).

As such, we can assume on the Intellectualist account, motor acuity is responsible for the fine-grained details[8] involved in the execution of skilled actions. Moreover, though motor acuity is necessary for the successful instantiation of a skilled action, it's important to notice that motor acuity is not knowledge involving or intelligent. Motor acuity, according to S&K, is simply the analogue of perceptual acuity[9]: a process that can undergo improvements as a result of experience but which is neither the result of attentive practice nor is it under voluntary control.[10] According to S&K, the problem with much philosophy and cognitive science is that "motor skills have been incorrectly identified with the part of skill that is not knowledge" (p. 15). That is, motor skills have been identified with procedural knowledge but, according to S&K, procedural knowledge is not knowledge at all. It is just motor acuity: a causal, subpersonal, phenomenon of motor mechanisms tuning up in a strictly bottom-up manner. In short, for S&K, skill combines intelligent guidance by propositional knowledge with the noncognitive, basic,

[7] See Fridland (2014) for an illustration of the importance of fine-grained motor control in giving an adequate account of skill.

[8] When I use "fine-grained", I have in mind both the parameters and time-scale of movement. As such, fine-grained movements are evident in both the millimeter and microsecond adjustments that are characteristic of skilled action.

[9] S&K write that "motor skills have an acuity component that is directly analogous to perceptual acuity" (p. 16).

[10] As S&K write, "Shmuelof et al. have recently coined the term "motor acuity" to describe the practice related reductions in movement variability and increases in movement smoothness….Such adaptions are not the acquisition of something that is characteristically manifest in intentional action, i.e., they are not the acquisition of skills" (p. 15).

subpersonal, low-level motor and perceptual abilities. The propositional bit of skill is knowledge involving while the motor acuity bit is not.

For my purposes, the relevant aspect of S&K's hybrid theory that is worth questioning is their construal of motor acuity. That is, it is worth investigating the truth of S&K's claim that motor acuity is a more or less bottom-up, brute-causal process that does not require epistemic, cognitive, semantic, personal-level, or agentive explanations. In the following, I will consider evidence, which indicates that such a simple, causal account of the detailed kinematics of automatic motor processes both oversimplifies and mischaracterizes the nature of the motor phenomena involved in skilled action.

1.2 Papineau on sporting skill

In a similar spirit, Papineau argues that there are three reasons for thinking that the automatic motor processes that unfold during sporting skill are not guided by conscious control[11] and, thus, are reflex-like. First, there is the speed at which many sporting skills are executed—a speed that makes it practically impossible for the slow, deliberate, conscious system to be involved in their implementation (Papineau 2013, p. 178). Second, there is the fact that the unconscious dorsal stream and not the conscious ventral stream has been shown to be responsible for the online visual control of overlearned movements, such as reaching and grasping (Milner and Goodale 2006, 2010). Accordingly, Papineau argues that it is much more likely that the unconscious dorsal stream facilitates successful motor skill execution rather than conscious, personal-level, ventral stream processes. Thirdly, Papineau appeals to the fact that, at least sometimes, conscious thought interferes with the smooth and easy flow of motor skill (Beilock and Carr 2001; Beilock, et al. 2002; Beilock 2007, 2010). For these reasons, Papineau concludes that the motor processes executed in sporting skill are not cognitive or conscious phenomena but, rather, largely a matter of reflex.[12] He writes:

> We have seen ample reason to think that top-level batting is more like an automatic reflex than any consciously controlled sequence of movements. The basic facts of timing, plus the evidence rehearsed in the last three sections, all argue that the execution of a specific shot in response to the bowler's delivery is an automatic reaction honed by thousands of hours of previous practice (p. 184).

Papineau does not deny that conscious intentions can and do effect the execution of automatic, expert skills but he is clear that intentional states only impact automatic basic actions in an indirect way. According to Papineau, conscious intentions can set the parameters for the action-control system such that the right automatic motor

[11] It seems safe to assume that for Papineau, "conscious" does not just mean "phenomenal" or "experienced" but something more like "an intentional, personal-level states that one is a aware of being in".

[12] For a response to the claim that these considerations entail that skilled bodily actions are mostly non-conscious, see Shepherd (2015).

routine is triggered in the appropriate situation. The story he gives for how this might happen is the following:

> This phenomenon strongly suggests that long-term intentions do their work by adjusting the state of the basic action-control system. The formation of an implementation intention reconfigures this system so that it will trigger behaviour B when circumstance C is next encountered. After that the operation of the basic action-control system can proceed in its normal automatic manner (p. 190).

When applied to sporting skill, the account looks like this:

> At any stage of an inning, a competent batsman will have assessed the situation and formed a view about how to bat—a conscious *intention* to adopt a certain strategy. As with any intention, this will then set the parameters of the basic action-control system. It will direct that system to bat aggressively, say. It will take one *raft* of conditional dispositions from the batsman's repertoire, and reconfigure that basic control system so that it embodies just those dispositions…Having been so reset, the basic action-control system will then respond accordingly, without any further intrusion of conscious thought" *Emphasis in original,* (2013, p. 191).

For Papineau, what's crucial is that the intention to bat in certain way, e.g., aggressively, selects a certain class of dispositions, i.e., aggressive batting dispositions, which will run automatically in response to the appropriate environmental stimuli. One can think of Papineau's proposal in the following manner: strategic intentions initiate the selection of a relevant action folder, which contains a set of automatic motor routines that have been developed through practice, training, drilling, etc. Once the folder is selected, the automatic motor routines within it run autonomously in a more or less fixed, reflex-like manner.[13]

What's clear from this picture is that if we want to identify a cognitive component of sporting skill, that component will be the conscious, personal-level strategic intentions that direct or set the parameters for the action-control system. The other phenomena involved in motor skill, i.e., automatic basic actions, are characterized not in semantic or cognitive terms but as learned but fixed reflexes. These automatic motor processes are not directly impacted by personal-level conscious intentions or knowledge but, rather, run autonomously in a bottom-up manner once they are primed by the action-control system and cued by the right situational features. In short, for Papineau, since conscious control is not involved in directing or guiding the fast automatic processes of motor skill instantiation, those

[13] For a similar account of intentions organizing action in a top-down manner, by setting the parameters which prime or trigger automatic action execution, see Wu (2013). Wu writes, "We thus act intentionally. In playing the piano, the automaticity aimed for is that the specific notes played need not be represented in one's intention. "Parameter specification" is automatic because no top-down modulation at the level of intention is required to specify the specific notes played, the ordering of fingering and so forth. Certainly, in learning that passage, one can act with a changing set of demonstrative intentions, say to play that note with these fingers, and this is attentionally demanding. One has to attentively focus on relevant notes or relevant keys. But once the piece is mastered, setting those parameters is automatic" (p. 18–19).

processes need not be cashed out in higher-order, personal-level, conceptual or intentional terms.

We should notice that to challenge Papineau's position, it is not necessary to deny his claim that conscious processes do not guide or control the online execution of automatic motor routines directly. Rather, we need only question whether the automatic motor routines themselves are brute-causal or mechanistic as a result of not being under the direct control of consciousness. That is, we can question the legitimacy of Papineau's move from "not controlled by consciousness" to "reflex-like". Specifically, we should ask if the lack of conscious involvement in the fine-grained execution of automatic motor routines entails that the automatic motor routines constitutive of motor skills are reflex-like or mechanistic in nature. I will first forward this more basic challenge to Papineau's view and later demonstrate that, likely, Papineau is wrong even about conscious, personal-level intentional states not being directly involved in the online adjustments and modifications manifest in automatic motor skill execution.

2 Motor control, motor acuity, and reflexes

In this section, I will first consider the implications and commitments that follow from both S&K's and Papineau's hybrid accounts of skill. In doing so, I will highlight five features that ought to characterize motor control, if the hybrid accounts are correct. Together, these accounts predict that motor control is: (1) ballistic, (2) invariant, (3) independent of general action trajectories, (4) insensitive to semantic content, and (5) independent of personal-level intentions. I take it that any hybrid view of skill where the intelligence of skill is cashed out in personal-level intentional states and the motor component is characterized as brute and automatic will be committed to some combination of these features. As such, it is significant that all of the below features fail to characterize skill.

2.1 Implications of S&K's account

There are three major implications of the S&K hybrid view of motor skill that can be challenged on the basis of current empirical evidence supporting optimal control theory. The first is a strict independence between propositional knowledge and motor acuity. The second is that improvements in motor skill will yield a uniform reduction in movement variability, and the third is that motor acuity is insensitive to higher-order goals.

As I outlined above, a principle commitment of S&K's view is that propositional knowledge and motor acuity are independent components of motor skill. If this view is correct, then it should be possible to identify, characterize, and account for the non-epistemic aspects of motor skill, i.e., motor acuity or what has often been referred to as procedural knowledge, in a way that is largely independent of propositional knowledge. Specifically, we should be able to give a full account of motor acuity by citing only causal relations between it and propositional states.

Since S&K follow Shmuelof et al. (2012) in their construal of motor acuity, it seems reasonable to assume that S&K take on board the core distinction forwarded by Shmuelof and colleagues between processes responsible for motor acuity and processes responsible for task success. As Shmuelof et al. write, "[m]otor skill can be assessed at the levels of task success and movement quality" (2012, p. 578). They go on to "propose that motor skill acquisition can be characterized as a slow reduction in movement variability, which is distinct from faster model-based learning that reduces systematic error in adaptation paradigms" (2012, p. 578). As we'll see below, Shmuelof and colleagues identify the slow reduction of movement variability with motor acuity, which leaves the faster model-based learning to be cashed out in terms of propositional knowledge (presumably, alongside other more familiar kinds of skill-based propositional knowledge, like, e.g., knowing a way to initiate an action and knowledge of what one is doing).[14]

This follows from the S&K account since S&K highlight only two components of skill: the propositional component and the motor one. And since the motor component of skill is identified with motor acuity, we are forced to conclude that the representations responsible for task success in adaptation paradigms are propositional in nature.[15] Accordingly, for the purpose of this discussion, we can identify the fast, model-based improvements observed in skill learning as acquiring knowledge of a way to φ, or learning a more-or-less general, stable trajectory, strategy, or movement sequence with which to achieve task success under various circumstances. This propositional knowledge, which is cashed out in terms of internal representations or forward models, should be responsible for an agent's ability to compensate for perturbation or overcome systematic error in a variety of circumstances; that is, this propositional knowledge should be responsible for task success.

In contrast to the propositional knowledge component of skill, Shmuelof and colleagues maintain that motor acuity is a matter of increasing skill by reducing the variability of the movements constitutive of motor tasks and, thus, increasing movement quality. In fact, motor acuity can improve even after task error has been reduced to zero.[16] For Shmeuloff and colleagues, as motor acuity increases, the amount of variability in the trajectory of a skilled movement decreases. From this it follows that if fine-grained motor execution can be accounted for in terms of motor acuity alone then, in learning, we should expect to see on overall, uniform reduction in the variability of the kinematic details of automatic movements comprising

[14] This also seems like a reasonable interpretation of S&K, since Haith and Krakauer (2013a) endorse a view where, following Korenberg and Ghahramani (2002), model-based motor learning can be construed as belief-like.

[15] Adaptation learning can be understood as follows: "In these paradigms, subjects experience a perturbation of their hand during reaching or pointing movements: lateral displacement by prisms, rotation of movement direction, or lateral forces applied by a robot arm. Specifically, these paradigms have focused on adaptation, a form of learning characterized by gradual improvement in performance in response to altered conditions." (Krakauer and Mazzoni 2011, p. 1).

[16] "Learning tasks of this type do not generally have a built-in limit of performance: there is no systematic error to reduce to zero, and final performance is different from baseline" (Shmuelof et al. 2012, p. 579).

skilled actions. That is, once the way, trajectory, motor sequence, or strategy has been learned (i.e., that part of learning that is concerned with task success and is attributable to propositional knowledge) then when it comes to the execution of a motor skill, on the S&K view, one should observe a uniform reduction in movement variability.

Lastly, if S&K are right about motor acuity, then it is worth pointing out that the fine-grained execution of automatic motor routines should not be directly sensitive to the semantic content of higher-order, intentional, personal-level goals. This is because if motor acuity is construed as a low-level, non-knowledge-involving, bottom-up, brute-causal process, and if motor acuity is responsible for the detailed kinematics of motor skill instantiations, then the detailed kinematics of motor skills should not have the ability to systematically respond to various conceptual, semantic, intentional and otherwise, higher-order cognitive, personal-level contents of goal-directed representations. This follows in a straightforward manner from the idea that brute-causal processes, like those involved in e.g., water running down hill, billiard balls colliding, or digestion, are the wrong kinds of states to integrate with or be sensitive to intentional content. In fact, this commitment is fundamental to the distinction between physiological or physical systems and psychological or semantic ones. That is, this distinction really just points to the difference between systems that need to be explained in semantic or epistemic terms versus those that can be accounted for in brute-causal ways. At this point, it is important to note that in order for S&K's distinction between motor acuity and propositional knowledge to work, they must endorse a view where low-level motor states like those involved in motor acuity are importantly and fundamentally unlike propositional knowledge when it comes to requiring cognitive, semantic or epistemic explanations. If they do not commit to the robust distinction between brute-causal and semantic-psychological explanations, then their basic contrast between motor acuity and propositional knowledge will turn out to be rather pallid.

In the following section, I will demonstrate that all three of S&K's predictions are challenged by optimal control theory. That is, there is evidence that the detailed movements constitutive of motor skills do not undergo a uniform reduction in variability but, rather, reduction in variability is relative to task-relevant dimensions of movement execution. Second, the lack of correction for task-irrelevant dimensions of movements indicates that the detailed motor kinematics involved in skilled motor execution and the general trajectories responsible for task success are not in fact independent of one another. Specifically, the intelligent online correction of only task-relevant dimensions of movement is incompatible with a view that holds that trajectories are set by one system and then executed mechanically by another. Third, since task-relevant and irrelevant dimensions of movement are not pre-determined by an independent motor planning, trajectory-setting system, it is plausible that a sensitivity to personal-level goals accounts for the motor control system's capacity to differentiate task-relevant and task-irrelevant dimensions of skilled movements.

2.2 Implications of Papineau's account

Though Papineau does not articulate which features he takes to be most relevant for characterizing motor skills as reflex-like, we can reasonably assume that the following four properties are likely central to any account of motor skills as reflex-like: (1) reflexes are insensitive to the content of personal-level goal states. So, as discussed above, though intentional states might set the parameters for triggering motor routines, the motor routines themselves should be internally unresponsive to the particular features of a task that are specified by the goal. That is, the task or end should be set in such a way that automatic basic actions can simply execute it, but not adjust or adapt in any way that would require or indicate an understanding of the goal. And (2), the semantic insensitivity of reflex-like motor skills entails that strategic intentions and automatic basic actions are fundamentally independent of one another. That is, one should be able to produce a complete characterization of each without an account of the other. Specifically, one should be able to give a full account of automatic motor routines without any more than a causal appeal to intentional, personal-level states. Additionally, it seems safe to assume that an account that characterizes skills as reflex-like will likely be committed to the idea that (3) reflexes run in their entirety once they are triggered. That is, reflexes are difficult to intervene upon once they have begun. In this sense, reflexes are ballistic. And the last feature that appears relevant for classifying motor skills as reflexes is that (4) the instantiation or execution of an automatic basic action is more-or-less fixed or invariant. That is, we should expect very little flexibility or variability in the execution of a reflex—reflexes run the same way every time they are triggered. As such, if automatic motor routines are reflexes then they should likewise be invariant.

Features (1) and (2) follow directly from Papineau's proposal concerning the structure of the basic action-control system and its relation to strategic intentions. That is, Papineau is clear that he takes automatic basic actions not to be directly impacted by conscious intentions at the personal-level. This lack of direct interaction between automatic basic actions and strategic intentions entails that the two phenomena are categorically independent of one another even if intentions have an indirect impact on automatic processing via priming or parameter setting. As such, if Papineau is right then basic actions ought not to run in a way that reflects a responsiveness to semantic content, but, rather, the goal state ought to be set by strategic intentions and then executed by the basic-action system in a more or less brute fashion. After all, that's the way reflexes run—they are independent of and sometimes even contrary to personal-level goals.

The feature of ballisticity also seems to be a plausible characteristic of motor routines if they are construed as reflexes. A "process is ballistic, just in case when the processor starts it cannot be stopped by any endogenous means." (Mandelbaum 2014). Though, Papineau does not explicitly endorse or highlight this feature of automatic basic actions, it is presumably worth exploring whether the motor processes involved in sporting skill run in a ballistic fashion. After all, it would seem that paradigmatic cases of reflexes, like the knee-jerk reflex (patellar reflex), blink reflex (corneal reflex), withdrawal reflex, or gag reflex, are all ballistic in this sense. That is, one cannot interrupt or inhibit the reflex once it has been triggered, even if, in some instances, the agent has some control as to whether or not the reflex is triggered in the first place.[17] Moreover, it is possible that sporting skills are ballistic, and that the hours upon hours of training and drilling required for achieving high-level expertise in a skill is partly a matter of creating the conditions under which a basic action will run to completion on its own, without the need for ongoing attention, monitoring or guidance. That is, it is possible that a large amount of training creates reflex-like motor routines that must run until completion once set in motion and it may be that this feature of basic actions is important for the automatization of motor skills.

Lastly, it would seem that a central, paradigmatic feature of reflexes is that they are inflexible, fixed, or invariant. That is, reflexes seem to be the kinds of processes that run the same way any time they are activated. If there is variation, one would expect it to be in the magnitude of the response, but certainly, the reflex itself seems to be a pretty fixed sort of thing. As such, if automatic basic actions are reflexes then we should expect very little variability in the particular manner or fashion in which automatic motor routines are implemented on various occasions. That is, when basic actions are activated, we should observe more or less invariant kinematic patterns unfolding as a response. Moreover, it would seem that the more variation or flexibility evident in automatic basic actions the less they would resemble reflexes.

As it turns out, none of the features that ought be observed if Papineau's hybrid view of sporting skill is correct are in fact observed in the automatic sensorimotor execution of goal-directed skills. In the following section, I will go into some detail about why these predictions about basic actions turn out to be false by reviewing empirical results that support optimal control theory.

3 Optimal control theory and hybrid views of motor skill

In this section, I will appeal to optimal control theory (Todorov and Jordan 2002; Liu and Todorov 2007; Todorov 2004) to challenge the commitment to motor acuity as a reflex-like basic action. I do not claim that optimal control theory is the only game in town, but as will become clear below, it is in a unique position to account for recent experimental evidence of intelligent kinematic variability in an elegant and straightforward fashion. Though I focus specifically on S&K and Papineau's accounts of motor skill, presumably, any hybrid view of skill will be committed to a combination of the features that their accounts forward as characteristic of skill. As we saw above, together, S&K and Papineau's hybrid theories of skill are committed to the following five features of automatic motor control:

1. Ballisticity
2. Invariance
3. Independent of general trajectories

[17] As Mandelbaum writes in describing ballisticity, "The proper input is not necessarily processed every time the input reaches the module, but once the processing starts, one cannot stunt it at will, either through top-down effort or via other roughly psychological means" (forthcoming, pp. 6–7).

4. Insensitivity to semantic content
5. Independence from personal-level strategic intentions

I will argue that none of these purported features of motor control apply to the automatic motor processes executed in motor skill instantiations.

3.1 Ballisticity

Though the motor processes involved in skill are automatic, it is an open question whether one ought to conclude from this that these processes, "once learned, are difficult to suppress, modify or ignore" (Shiffrin and Schneider 1977, p. 129). In fact, it seems that the notion that automatic processes are uncontrolled or uncontrollable is very difficult to sustain, if one begins by thinking about automaticity from the perspective of high-level motor skills such as tennis, gymnastics, or rugby instead of from the perspective of, e.g., perceptual processing. That is, if we start with skill, I think we will quickly conclude that the more skilled an automatic motor routine the more controlled it should be as well. After all, as Logan writes,

> Skilled performers are usually able to control their performance better than unskilled performers, even though their performance is likely to be more automatic. That is why we prefer to fly with experienced pilots rather than novices, why we feel more comfortable with experienced dentists and surgeons than with beginners, and so on (1985, p. 385).

Presumably, control should include the ability to inhibit a skilled action at will (the impacts of natural forces, such as gravity, notwithstanding). So, if control over high-level motor skills increases with expertise, then one should expect that an expert would be able to intervene, interfere, and inhibit an automatic motor process at almost any point in its unfolding. From this perspective, we should expect that, unlike reflexes or mandatory processes, the automatic motor routines that compose complex skills should not prove to be ballistic.

Empirically, this is what we find. Logan (1982) studied expert typists to determine whether expertise in typing, and the associated automaticity of expert typing routines, are difficult to inhibit once initiated. That is, Logan set out to determine if the automatic routines constitutive of typing skill were ballistic. Contra the expectations of those who held that automatic processes were difficult to control,

> Logan (1982) found that expert typists could successfully and quickly interrupt typing midword when hearing a stop signal; this indicates that the presumed automatic behavior of typing was not ballistic at the level of the word. Moreover, additional analyses demonstrated that skill level, as indexed by words typed per minute, was not related to stopping latency (Logan 1983). (Cohen and Poldrack 2008 p. 108).

Hence, Logan concludes that the automatic motor processes that underlie skilled typing are both automatic and controlled.

Cohen and Poldrack (2008) confirmed Logan's (1982) result by training a group of novices on a serial reaction time task (SRT). The participants trained until appropriate motor responses to various stimuli became immune to dual-task interference, a widely accepted sign of automaticity (Posner and Snyder 1975; Logan 1979). Cohen and Poldrack (2008) then tested the reaction time of participants when asked to inhibit their automatized responses. They found that there was "no change in the concomitant ability to inhibit motor response" (2008, p. 113). That is, the reaction time for inhibiting an automatized motor response did not increase as the task became automatized. Cohen and Poldrack (2008) conclude that, "these results contradict the proposition that automaticity is associated with a loss of control or development of ballistic movements" (p. 113). In short, there is significant empirical evidence to suggest that the automatized basic action routines that constitute motor skills are not ballistic.[18] This is the first reason to doubt that the automatic motor processes constitutive of motor skills are reflex-like.

3.2 Motor control as invariant

3.2.1 Reflex-like invariance

As we saw above, if the automatic motor routines comprising skilled actions are reflex-like, then we should expect them to be more or less invariant or fixed. However, this prediction does not square with the fact that, in general, "movements are inherently variable" (Haith and Krakauer 2013a, p. 12). The fact is that motor skills exhibit a significant amount of variability when instantiated on different occasions. As Todorov and Jordan write, "an especially puzzling aspect of coordination is that behavioral goals are achieved reliably and repeatedly with movements rarely reproducible in their detail" (2002, p. 1226). And they go on to say that,

> both the difficulty and the fascination of this problem [of motor control] lie in the apparent conflict between two fundamental properties of the motor system. 1: the ability to accomplish high-level goals reliably and repeatedly, versus variability on the level of movement details. (Todorov and Jordan 2002, p. 1226).

And this goes not only for unpracticed movements but for expert skills, as well (Bartlett et al. 2007). As Yarrow et al. (2009) report, "athletes fail to reproduce precise kinematic pattern when performing a particular sports-specific activity" (p. 586–7). As such, we can conclude that in sporting skill, we do not see the development of rigid, fixed or invariant movements with increased expertise. As

[18] Though, as Helen De Cruz has pointed out to me in personal communication, this evidence does not support the stronger claim that skilled agents are able to intervene upon or inhibit their actions more quickly than novices. It only supports the claim that skilled actions are not ballistic. Further research is needed to support the, to my mind, plausible prediction that with expertise, inhibitory control over skilled action increases.

such, we have a second reason to doubt the proposal that the automatic basic actions constituting embodied skill performance are reflex-like.

We should notice that the inherent variability of goal-directed movement seems to be the motor system's optimal solution to its massively redundant structure. Though, intuitively, we might expect that the best way to achieve the same goal in similar circumstances is to execute the very same movements, it turns out that the structure of the motor system makes such invariant or reflex-like movements sub-optimal. In fact, the very opposite appears to be true: variability is the best way to take advantage of the degrees of freedom afforded by a largely redundant, noisy, motor system that can achieve any motor goal in a large variety of ways by modifying variables such as force, acceleration, angle or joint position during movement.[19] Accordingly, we see that even in practiced sporting skills, the kinematic details of movements are not precisely repeated in fixed ways, but retain a fair amount of variability and flexibility.

In addition to the variability of automatic motor routines, we should also notice that flexibility should be guaranteed by an increase in expertise. As I emphasized above in relation to ballisticity, we should expect that as skill increases, so too does flexibility and control. In the context of the variability of skilled movement, we should expect flexibility to be manifest in the appropriate online modification of automatic basic actions.[20] That is, the more skilled an agent, the more we should expect her to be able respond appropriately to unexpected circumstances and adjust her automatic movements appropriately, in flexible and controlled ways.[21] After all, we should expect the expert to be able to modify and adjust her skilled motor executions in ways that a beginner is unable to.[22] Accordingly, the more skilled an agent, the less reflex-like her skilled, automatic, basic actions should be.

However, if automatic basic actions become like reflexes through training then this sort of flexibility and control would be impossible. In fact, a reasonable way to interpret Papineau's claim about automatic basic actions is to think of them as feedforward, model-free, open-loop processes. Open-loop motor control processes are developed through trial and error reinforcement learning and, though cheap to acquire, remain unfortunately inflexible (Haith and Krakauer 2013b). For instance, to change a learned open-loop motor routine, one needs to start from scratch; one cannot simply adjust various aspects of the process in response to relevant information about one's body or one's environment. Further, as Todorov (2004) argues,

[19] As Haith and Krakauer (2013a) write, "far from viewing redundancy as a problem, redundancy should actually be regarded as a positive thing. It makes it easier to find solutions to a given task and allows goals to be achieved more flexibly and robustly. Redundancy, therefore, makes life easier for the motor system to develop adequate means of control and in general enables superior control strategies" (p. 9).

[20] For similar claims cashed out in an account of the relationship between intentions and actions, see Shepherd (2014).

[21] As Haith and Krakauer point out, "there is no need to wait for a large perturbation to prompt an adjustment of one's movement. Even small deviations from expected trajectories should prompt a flexible change in motor commands" (2013a, p. 15).

[22] Recall that, as we saw above, overcoming perturbations in adaptation paradigms is attributable to model-based representations (i.e., internal forward models) and not to open-loop, model-free processes.

> [O]pen-loop optimization has two serious limitations. First, it implies that the neural processing in the mosaic of brain areas involved in online sensorimotor control does little more than play a prerecorded movement tape—which is highly unlikely. Second, it fails to model trial-to-trial variability" (p. 907–908).

By drawing our attention to the inflexibility of open-loop processes, I don't mean to insist that open-loop control is not involved in skilled actions in any way. Presumably, such simple reinforcement learning would be useful both for reducing the computational demands required for model-based motor control and for exploiting the multitude of instances that an expert has performed a given motor routine in practice.[23] However, given that simple reinforcement learning is inflexible, motor skill instantiation would seem to require the ready possibility of overriding open-loop processes by other elements of the motor control system, which are themselves sensitive and responsive to various changing features of the environment, one's body, and one's goals. But again, this would mean that, in skill, even where open-loop control is involved, automatic motor processes are not reflex-like, fixed, or inflexible—that is, automatic basic actions are not simply a matter of appropriately triggered, model-free, open-loop motor control policies.

3.2.2 Reduction in variability

If procedural knowledge is really just a matter of motor acuity, then, as expertise grows, we should expect to see an overall reduction in the variability of movements constitutive of motor skill. This is because motor acuity should not be sensitive to the semantic content of goal states, which will specify and update which aspects of a movement are goal-relevant and which goal-irrelevant. However, this prediction is not born out by the empirical evidence. The fact is that as motor control develops, it does not undergo a uniform reduction in variability but, rather, variability is reduced in task-relevant dimensions of movement more than in task-irrelevant dimensions (Bernstein 1967; Cole and Abbs 1986; Scholz and Schoner 1999, 2000; Domkin et al. 2002; Todorov and Jordan 2002; Nagengast et al. 2009).

As Todorov and Jordan (2002) explain,

> trial-to-trial fluctuations in individual degrees of freedom are on average larger than fluctuations in task-relevant movement parameters—motor variability is constrained to a redundant subspace (or 'uncontrolled manifold') rather than being suppressed altogether (p. 1226).

Reduced variability in task-relevant kinematic details but not in all dimensions of movement conforms to what is called the Minimum Intervention Principle (MIP). According to this principle, agents "only correct perturbations that interfere with the achievement of task goals. If a perturbation is irrelevant to the task, for instance, if your elbow is knocked during a reaching movement without affecting your hand position then there is no need to correct for it—jut maintain the new elbow posture during the rest of the movement" (Haith and Krakauer 2013a, p. 16).

[23] For more on this, see Haith and Krakauer (2013b).

When applied to motor skill, we see that contra the predictions of S&K, the automatic sensorimotor execution responsible for the fine-grained movements constitutive of motor skill do not undergo a uniform, undifferentiated, brute, reduction in variability. Rather, as Yarrow et al. (2009) explain, though movement variability undergoes a general reduction through practice, the reduction is not uniform among task relevant and task irrelevant dimensions. In fact, “stabilization of movement is greater for those aspects of posture that contribute directly to desired outcome” (p. 586).

From this it follows that in motor skill execution, the motor control system must be able to differentiate between those aspects of a movement that are relevant for task success and those, which are not. But this means that the reduction in movement variability observed during motor skill learning cannot be the result of a brute, tuning-up process achieved through blind repetition. And this means that motor acuity alone cannot account for the fine-grained automatic motor processes that unfold in skilled action. This is because motor acuity predicts a uniform reduction in variability across all dimensions of movement; a reduction that is achieved in a non-semantically sophisticated way. But what we find empirically is a reduction in variability that is differentiated between task relevant and task irrelevant dimensions of skill.

3.3 Trajectory and motor control are not independent

The above results supporting optimal control theory also challenge the proposed independence of trajectory (knowing a way to φ) and sensorimotor execution predicted by S&K’s theory. The fact is that optimal control theory demonstrates that the detailed kinematic strategies executed in motor skills do not blindly implement some general, pre-planned trajectory but, rather, unfold in an intelligent way. I will discuss two studies, which are particularly important for demonstrating that trajectory and detailed motor execution are not independent.

First off, Liu and Todorov (2007) demonstrate “that corrections for target perturbations introduced late in a reaching movement are incomplete” (p. 9354). Importantly, they are able to show not only that certain perturbations remain uncorrected but that these perturbations remain uncorrected because they are irrelevant for task success and not simply because there is no time to correct them. This finding supports the notion that fine-grained sensorimotor control is flexible insofar as corrections are made in an intelligent way—not simply to conform to a pre-determined trajectory, but in order to achieve one’s goal. That is, if a correction is unnecessary for task-success, even if it was part of an original motor plan, after perturbation, it remains uncorrected.

The flexible nature of sensorimotor control is further confirmed by Deidrichsen (2007) who shows “that both feedback control and adaptation change optimally with task goals” (p. 1675). In his study, Diedrichsen had

> participants reach with two hands to two separate spatial targets (two-cursor condition) or used the same bimanual movements to move a cursor presented

> at the spatial average location of the two hands to a single target (one-cursor condition) (p. 1675).

In both the feedback control paradigm and adaptation task, Diedrichsen demonstrated that movements were corrected for and adapted to in a way that reflected task goals and not a fixed, pre-determined trajectory. Diedrichsen showed that in the bimanual, two-cursor condition, only the movement of the hand that was required for achieving task success underwent adaptation and was corrected for. The other hand, since it was irrelevant for task-success, was not modified. In contrast, in the two hands, one-cursor condition, both hands were corrected for and adaptation occurred for both, as adjustment of both hands was necessary for achieving the goal. This study supports the idea that motor control is sensitive to task goals both at the sensorimotor execution and adaption level.

Together, these studies suggest that the detailed movements constitutive of motor tasks do not rigidly execute a determinate trajectory but change and adjust online in an optimal way to achieve task success. As Todorov and Jordan (2002) explain, "the optimal strategy in the face of uncertainty is to allow variability in redundant (task-irrelevant) dimensions. This strategy does not enforce a desired trajectory, but uses feedback more intelligently, correcting only those deviations that interfere with task goals" (p. 1226).

We should notice that these results entail that action trajectory planning and execution are not independent. This follows from the above results because if the trajectory were planned prior to and independent of motor execution, then corrections in execution should conform to the pre-planned trajectory. That is, the relevant and irrelevant dimensions of the movement would not be determined online by the motor execution system but, rather, fixed by the system responsible for planning and selecting the appropriate trajectory. Since we see that movements are not corrected in a rigid way so as to conform to an initially planned trajectory but are continuously adjusted in order to achieve success at a given task, we can conclude that, contra S&K's prediction, propositional knowledge and motor acuity, or knowing the way to φ, and implementing the motor details in order to φ, are not independent phenomena. As Todorov and Jordan argue,

> This body of evidence [supporting optimal control theory] is fundamentally incompatible, with models that enforce a strict separation between trajectory planning and trajectory execution. In such serial models, the planning stage resolves the redundancy inherent in the musculoskeletal system by replacing the behavioral goal (achievable via infinitely many trajectories) with a specific 'desired trajectory'. Accurate execution of the desired trajectory guarantees achievement of the goal, and can be implemented with relatively simple trajectory-tracking algorithms. Although this approach is computationally viable (and often used in engineering), the many observations of task-constrained variability and goal-directed corrections indicate that online execution mechanisms are able to distinguish, and selectively enforce, the details that are crucial for goal achievement. This would be impossible if the behavioral goal were replaced with a specific trajectory (2002, p. 1226).

In short, trajectory planning and motor execution are not independent of one another. Accordingly, we can reject S&K's proposal that propositional knowledge, or that part of motor skill that is relevant for task success or trajectory planning, and motor acuity, that part of motor skill that is relevant for the quality of movements implementing a motor trajectory, are autonomous components of motor skill. It seems that if we want to understand the fine-grained kinematic details that unfold during motor skill execution, we have to do so by doing justice to the intelligent ways in which the motor control system functions. That is, we will not understand motor skill, if we insist that the automatic movements that are constitutive of skills rely on brute-causal motor processes that are incapable of adjusting and responding to situational demands in appropriate flexible, semantically integrated, and controlled ways.

3.4 Is motor control sensitive to semantic content?

The last question that we must ask then is this: if task-relevance and irrelevance is not determined prior to execution by an independent motor plan or trajectory, then how are those features determined? It seems that the simplest and most straightforward answer is that the motor control system is able to differentiate between task-relevant and task-irrelevant dimensions of movement by having the capacity to respond directly and flexibly to task goals. Accordingly, and as optimal control theory holds, the ability to differentiate between task-relevant and task-irrelevant details of a movement is accomplished by a sensorimotor control system that is directly sensitive to the semantic content of personal-level goals. As Todorov (2004) describes, "At the heart of the framework is the relationship between high-level goals, and the real-time sensorimotor control strategies most suitable for accomplishing those goals" (p. 907).

On optimal control theory, it would follow that the motor control system that is responsible for executing the detailed kinematic strategies required for implementing person-level goals, like, e.g., reaching for a glass of water, writing a sentence on a blackboard, or doing a cartwheel, is itself sensitive to the content of intentional states. That is, the motor control system is not simply executing some fixed strategy that has been pre-selected for it by the cognitive system but, rather, the motor control system differentiates what is and is not relevant for achieving task success by being directly responsive to higher-order, personal-level goals. As the goals or circumstances change, the sensorimotor system can make online adjustments in a flexible and intelligent manner, implementing control at various levels.[24]

3.5 Independence of intentional states and motor control

Importantly, the semantic coherence between goal states and the motor control system that executes them makes holding a hybrid view where intentions are strictly

[24] For a preliminary account of how personal-level intentions and the motor representations involved in skilled motor routines might be related see Butterfill and Sinigaglia (2014). For a response to their view, see Mylopoulos and Pacherie (forthcoming).

independent of and only causally related to the triggering of appropriate motor routines in appropriate situations impossible to hold. That is, the best evidence we have indicates that fine-grained, automatic motor processes instantiated in motor skills are not simply causally connected to intentional states but, rather, continue to be semantically sensitive and responsive to personal-level goals throughout execution. It is because of this responsiveness to personal-level intentional states that we are able to adjust and correct movements *en situ* in an optimal way, differentiating between task-relevant and task-irrelevant movements and making adjustments appropriately along the way. But the integration of task goal and automatic motor control is anathema to a picture of motor skill that holds a strict functional dichotomy between intentions or plans on one level and motor execution on another.

4 Conclusion

I hope that it has become clear that a hybrid view of skilled bodily action where the intelligence of skill is cashed out in propositional, intentional terms and motor control is characterized in bottom-up, brute-causal, unintelligent ways is unsustainable. Instead of thinking of independent intentional states and automatic reflex-like basic actions or of independent action trajectories and the execution of those trajectories by processes of motor acuity, it seems that we must revise our view of skill in order to reflect findings, which show that even those processes responsible for the automatic, low-level, fine-grained sensorimotor executions of motor skills are sensitive to high-level goals.

This fact propels us directly into a challenge that has recently been coined, the "interface problem" by Butterfill and Sinigaglia (2014). That is, the fact that motor control shows ongoing sensitivity to semantic contents at the personal level requires us to produce an account of how it might be that personal-level, conceptual, intentional states with semantic contents communicate with motor representations that are likely subpersonal and coded in a non-propositional, non-conceptual format.[25] The kind of dynamic, online communication between intentional states and motor representations that optimal control theory suggests obtains entails that any solution to the interface problem must address not only how intentional states play a role in the appropriate selection of motor representations but how the two kinds of states become integrated in such a way that creates coherent, successful, continuous action despite our ever-changing goals and the ongoing perturbations of the environment. In short, any satisfactory account of the interface problem must address not just how motor representations are triggered by intentions, but how motor representations are continuously connected to goal representations in a semantically coherent fashion throughout skill execution. We might call this the

[25] For arguments as to why these states should be thought of as representing information in different codes, see Butterfill and Sinigaglia (2014), Mylouplous and Pacherie (forthcoming), and Levy (forthcoming).

“dynamic interface problem” and despite recent efforts to solve the interface problem, a solution to this more ubiquitous challenge remains outstanding.[26]

All of these considerations point to the fact that an adequate account of skill will require a substantive account of control not only at the intentional and motor level, but also a robust theory of the integration between the two. Such an account might itself be considered to be an account of control, that is, such an account may provide us with a way of understanding the difference between more and less controlled actions. As Josh Shepherd offers, we might construe control as a property of certain kinds of flexible and repeatable actions; actions where, under various circumstances, motor representations fulfill the intentions that guide them (2014). In this way, the more integration there is between intentional and motor states, the more controlled an action would be. Accordingly, an answer to the dynamic interface problem may give us an account of controlled action, in general. As such, it would seem then that any adequate account of the control characteristic of skilled actions (control, a la Shepherd) will require substantive connections between control at the intentional and control at the motor level.

In short, like most dichotomies, the one’s that are proposed by hybrid views of motor skill turn out to be false. The motor control system is not simply a brute-causal, bottom-up system that becomes tuned through simple repetition, and which is set or triggered by cognitive, intentional, personal-level states. The control characteristic of skilled actions, as it turns out, is a lot more complicated than that.

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[26] See Mylopoulos and Pacherie (forthcoming) for convincing reasons why the Butterfill and Sinigaglia (2014) demonstrative solution to the interface problem is left wanting. However, the considerations above also put pressure on Mylopoulos and Pacherie (forthcoming) who have not quite given us a way to understand dynamic interfacing.

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