

The Sense of Agency and Its Role in Strategic Control for Expert Mountain Bikers

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Much work on the sense of agency has focused either on abnormal cases, such as delusions of control, or on simple action tasks in the laboratory. Few studies address the nature of the sense of agency in complex natural settings, or the effect of skill on the sense of agency. Working from 2 case studies of mountain bike riding, we argue that the sense of agency in high-skill individuals incorporates awareness of multiple causal influences on action outcomes. This allows fine-grained differentiation of the contributions of self and external factors to action outcomes. We further argue that the sense of agency incorporates prospective awareness of actions that are possible in a situation and awareness of the limits of control. These forms of sense of agency enable highly flexible, context-sensitive strategic control, and are likely to contribute to high inter-individual variability in responses to complex tasks.

Keywords: expertise, prospective awareness, sense of agency, sense of control, skill

In July 2014 two of the authors, Kath and Wayne, were riding at the Ourimbah mountain bike track in the Central Coast region of New South Wales, Australia. Kath is an experienced mountain bike rider, whereas Wayne has very limited experience riding off-road. The plan was that Kath would teach Wayne some basic mountain bike riding techniques. One of the sections of the Ourimbah course that Wayne found challenging was a rocky ascent with tight uphill turns. This required maneuvering up through the rocks and

around the corners at low speed, maintaining balance and control while timing pedal strokes to avoid crunching the pedals onto rocks. This was a nervous process for Wayne because he was not sure whether he could ride the section. Like many novices he has difficulty maintaining balance and control at slow speeds. A point came where Wayne felt that he had run out of options: he did not have enough momentum to get around the next rock or enough space to pedal. Anticipating that he would come to a stop and fall over, he unclipped and put his foot down, and then had to walk the rest of the section. Behind him Kath was ‘trackstanding’—staying balanced while motionless. When he was clear, she rode smoothly and easily up the path.

In this article we examine some important relations between skill and the sense of agency (SoA). We argue that not only does skill improve action abilities, but it also improves action awareness, which, in turn, facilitates action control. Unsurprisingly, Kath possesses a much more highly developed action repertoire for mountain biking compared to Wayne. But Kath also exhibits a more highly developed awareness of her actions and abilities in relation to the situation, which allows her to adjust to changing circumstances and employ flexible strategic control to improve her performance.

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We thank the audience at the 10th Conference of the Australasian Society for Cognitive Science, 2014, for helpful feedback on an earlier version of this article. Questions asked by Glenn Carruthers, Liz Schier, Günther Knoblich, and Tim Bayne have prompted us to clarify and elaborate our account. Thanks also to Andrew Geeves and Kellie Williamson, who have influenced our views and methods. Thank you to Rosemary Barnes for her photo of the initial attempt at Croc’s Teeth, and to Reilly Hurst for providing the race image on behalf of RideCairns (www.ridecairns.com).

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Researchers have devoted little attention to the influence of skill on the SoA. Accounts of skill that emphasize automaticity suggest that highly skilled individuals will have minimal awareness of their actions (e.g., [Beilock & Carr, 2001](#); [Dreyfus, 2013](#); [Brownstein, 2014](#)). Recently, a number of authors have argued against this view, claiming that self-awareness can be enhanced in elite skills and can contribute positively to performance (e.g., [Sutton, 2007](#); [Montero, 2010](#); [Sutton et al., 2011](#); [Fridland, 2014](#); [Toner et al., 2014](#)). Contemporary accounts of the sense of agency, such as comparator-based accounts ([Frith et al., 2000](#); [Frith, 2012](#)), cue integration accounts ([Synofzik et al., 2008](#); [Moore & Fletcher, 2012](#)), and metacognitive accounts ([Carruthers, 2015](#)), neither explicitly address skill nor provide clear expectations for the effect of skill improvement on the SoA. Nor have researchers conducted much empirical investigation of the SoA that considers the role of skill. A notable exception is a study by [van der Wel et al. \(2012\)](#), which found that the SoA increased as performance on a novel sensorimotor task improved.

Research on the SoA has typically focused on abnormal cases, laboratory tasks probing basic action awareness capacities, and phenomenological characterizations of everyday actions. Unusual forms of action awareness, such as delusions of alien control in schizophrenia ([Frith et al., 2000](#)) and cases of illusory SoA in normal individuals ([Wegner, 2002](#)) can reveal breakdowns or distortions in the mechanisms of action awareness. Experimental methods such as probabilistic action-effect tasks have investigated basic capacities to detect causal relations between simple actions and simple events, such as a button press and the sounding of a tone (e.g., [Sato & Yasuda, 2005](#)). Philosophers on the other hand, as well as drawing on scientific evidence, have employed phenomenological analyses of everyday action experience to characterize the SoA. [Gallagher \(2000, 2012\)](#) and [Pacherie \(2007, 2008\)](#), for example, have presented influential characterizations of the SoA derived from pathological cases, experimental research and phenomenological descriptions.

Each of these sources of evidence has strengths and limitations. Pathological and illusory cases reveal some of the limits of the SoA, but provide only limited information about its

normal functioning among healthy individuals. Probing basic capacities using artificial tasks in the laboratory can address some aspects of normal functioning, but does little to cast light on the functioning of the SoA in everyday situations that demand complex action control. Phenomenological accounts can provide rich qualitative descriptions of the SoA in real-world conditions, but lack the rigorous controls possible in the laboratory. Nevertheless, phenomenological accounts have an important role to play: phenomenological descriptions of real-world action can help in conceptualizing the ‘big picture,’ contributing to theory development and rigorous controlled experimentation.

The phenomenological descriptions provided by philosophers who have commented on action and the SoA typically concern familiar everyday actions like answering an e-mail or responding to a knock on the door (examples used by [Gallagher, 2012](#)). Yet to gain a complete understanding of action control, it is necessary to consider advanced skills that involve highly developed and refined action control in real-world contexts. [Gallagher and Pacherie](#) briefly discuss cases that involve the SoA experienced by a skilled tennis player ([Pacherie, 2008](#), p. 210) and a skilled climber ([Gallagher, 2012](#), p. 29). But because advanced (nonacademic) skills are typically not part of the personal experience of philosophers, producing detailed phenomenological accounts in these kinds of cases requires collaboration with individuals who possess such skills. This is our approach here.

We focus on competitive mountain biking, which involves complex sensorimotor and strategic control at fast speeds. Our account centers on a case study of [Kath’s](#) experiences preparing for the final round of the Australian Gravity Enduro Series in Cairns. [Kath](#) has been involved in mountain biking for more than 15 years, giving her a perspective that combines a theoretical approach to skilled action with extensive personal experience.¹ Gravity Enduro is a type of racing where most competitors only see highly technical tracks a couple of times

¹ [Barbara Montero’s](#) work is similarly informed by personal experience as a ballet dancer (e.g. [Montero, 2010](#)). See [McIlwain and Sutton \(2015\)](#) for a methodological discussion of the value and challenges of research in which the researcher is a practitioner.

before racing against the clock (and each other). Riders are forced to develop ways of remembering and negotiating challenging and unfamiliar trail features within short time frames. These demands raise interesting questions about the processes involved in predicting, monitoring, and adjusting performance in situations that hold bone-breaking consequences for the poor execution of judgment or technique. These challenges are, of course, part of the attraction of the sport, which is growing in popularity.

We suggest that key elements of Kath's experience hold the potential to elucidate the nature and role of the SoA from a 'big picture,' qualitative perspective. We frame our discussion in relation to Pacherie's (2007, 2008) multilevel characterization of the SoA, which is perhaps the most comprehensive to date, and highlight similarities and differences between our approaches.

Hierarchical Action Control and the Sense of Agency

As a starting point, it is important to distinguish between long-term and occurrent SoA: the former refers to the sense of oneself as an agent over time, whereas the latter refers to the sense of agency experienced during action (Pacherie, 2007, p. 6). Occurrent SoA is often conceptualized as the sense of being the author of the action performed (Gallagher, 2000; Blakemore et al., 2002; Wegner, 2002; Pacherie, 2007, 2008; Moore & Fletcher, 2012). Pacherie's (2007, 2008) account focuses on occurrent SoA and on explaining what she describes as immersed and nonreflective agency, which encompasses 'how-awareness' and the 'sense of control.' How-awareness is awareness of the specific manner of performing an action (p. 198), whereas the sense of control includes both feeling in control of an action and the sense of exerting control of an action (p. 209). We will be mainly referring to the former when we use the term 'sense of control.'

Pacherie's (2007, 2008) account of the SoA extends the comparator theory (Frith et al., 2000), which is based on predictive models thought to govern motor control (Wolpert & Kawato, 1998). The central idea of the comparator theory is that when the observed outcome of an action matches the predicted outcome, the

movement is perceived as self-generated, whereas when a mismatch occurs, the movement is attributed to an external cause (Frith et al., 2000). Pacherie extends this idea by postulating a hierarchical model of action control that involves three levels: 'rational,' 'situational,' and 'motor' control (2008, p. 210). Action control involves a top-down cascade, though not all levels of control need be operative in every action. *Rational control* involves forming overarching action plans, typically before the performance of the action. *Situational control* involves applying an action plan to the demands of the immediate situation. *Motor control* involves specifying motor programs based on situational control.

Although the content, format, and processes of higher level control models are different from those involved in motor control, Pacherie claims that the core structure of control, involving prediction-outcome comparison, is likely to be similar (Pacherie, 2008, pp. 192–193). According to Pacherie (2008), the sense of control at the level of rational control is based on whether the action plan is successfully carried out, whereas at the level of situational control it is based on the match between the predicted and actual consequences of actions. Pacherie claims that motor control is automatic, and only contributes to the experience of control when large prediction-outcome discrepancies are present. Pacherie explains how-awareness in terms of the structure of the control hierarchy. Thus, how-awareness of rational control concerns the subgoals and subactions of the action plan, the how-awareness of situational control is awareness of movements of certain types, and the how-awareness of motor control is awareness of fully specified movements (p. 198).

Our account will support some aspects of Pacherie's theory and also suggest amendments and additions. Although we endorse the claims that (a) three levels of control play an important role in the SoA, and (b) model-based control is integral to the functioning of these levels of control, we argue that the SoA incorporates forms of awareness that Pacherie does not recognize and cannot be explained on the basis of comparator processes postulated by the comparator theory. We also address the contribution that the SoA makes to action control. Pacherie

notes that her account does not address this contribution,² but we contend that it is an important aspect of understanding the SoA. Finally, as noted earlier, we argue that skill learning enhances the senses of agency and control.

The Sense of Agency in Action

In October 2014 Kath rode down a section of trail called ‘Croc’s Teeth’ at Smithfield Mountain Bike Park in Cairns, Australia, for the final round of the Australian Gravity Enduro Series. She finished in fifth place in the Elite Female category in the series overall and in fourth place in this final round in Cairns. The bike and the trail were new to Kath, and the trail was ‘technical,’ meaning that it required advanced riding skills. In addition to competitive mountain biking and research, Kath also works as a cycling journalist and equipment tester. This means that she has experience with a broad range of bikes and trails, and often rides new (test) bikes in unfamiliar conditions. In what follows Kath reports on her experiences based on her field notes.

The Smithfield round of the Australian Gravity Enduro Series took place over two days, October 11 and 12, 2014. The event included six timed ‘stages,’ or routes, which linked together signed twists and turns through the tropical jungle. Croc’s Teeth was an obstacle that was part of stages two and four. Over four days and just under 10 hours of riding, Kath rode this short section of trail five times. When she first arrived at the obstacle, she got off the bike and looked at the terrain. She observed different pathways for riding through it, before remounting her bike and attempting to ride a line that went to the left before heading back toward the middle of the obstacle. She was not successful in cutting across from the left hand line on the first attempt at the maneuver, put her foot down to stop early, and walked her bike backup to the slope to try again. On consultation with a friend who was also practicing Croc’s Teeth, Kath adjusted the point she aimed for part way through the obstacle and was successful in riding it on the next attempt. On the third attempt, a day later, she slowed down to glance at the obstacle before rolling into it, but maintained momentum on her bike the whole time. Her goal this time was to ride it smoothly, with increased speed. The fourth attempt, on day

three, took place an hour before racing commenced. Having ridden the other race stages by now, which were far more technical, she felt quite comfortable on Croc’s Teeth this time. After practicing a more difficult track further up the hill that morning, she took ‘race stage two’ to get back to the start line and used this final run to relax and focus ahead of the race itself.

In the analysis that follows, we concentrate primarily on the first successful attempt at Croc’s Teeth, which involved a familiarization process that illustrates key features of the SoA. Kath’s initial adjustment to the bike and trail is especially revealing with respect to core processes of action control and awareness in this kind of skill (see Figure 1).

Although Kath’s experience and background knowledge informed her expectations about the characteristics of the new bike she used in Cairns, the performance of the bike could only be properly ascertained by riding it. During her first successful attempt at Croc’s Teeth, Kath’s attention was consequently shared between learning how to negotiate the trail and assessing how the bike would respond. An issue of concern was whether the brakes were sufficiently worn in to provide strong stopping power. Another key issue was the responsiveness of the suspension and whether it was properly tuned for Kath’s body weight and riding style. If the suspension was too stiff, it would feel jarring over rough obstacles and make the bike harder to control; too soft and it would bottom-out, once again failing to soak up the bumps properly. The geometry of a bike also has a big effect on its handling, making it twitchy or stable, and affecting the way that the rider needs to move to achieve the right body position during steep descents and other complex maneuvers. Kath was able to quickly get a feel for the bike. In about seven meters of trail she learned that the brakes were powerful and set up well in relation to her hands, the suspension was ‘buttery smooth’ (excellent), and the geometry gave the bike stable handling and placed her in an ideal body position with little effort. *“In that short run I learned enough about the feel and*

² She says, “Although this paper investigated the possible sources of the phenomenology of agency, it said next to nothing as to the possible causal role of awareness of action or feelings of agency.” (2007, p. 24)



Figure 1. Kath's first successful ride down Croc's Teeth. Her body is weighted toward the back of the bike to relieve pressure on the front suspension and indicating a slower, less relaxed approach to the descent. Photo: Rosemary Barnes.

handling of the bike that I confidently attacked each new obstacle from then on," she wrote (Bicknell, *in press*, italics in original) in a book chapter that examines this experience in more depth.

Understanding the specific handling characteristics of the bike allowed Kath to adjust her approach to riding the later features of that particular obstacle. As she continued to learn about *this* bike and *this* terrain, she adjusted the approach that she would use for the upcoming trails; with improved understanding of the bike she could attack them with more confidence, speed, and precision. She knew that on this particular bike she could ride more aggressively rather than cautiously over difficult obstacles, and that she would not damage the suspension riding over a steep drop further down the track. She could focus further ahead on obstacles down the trail, rather than compensating for the handling of the bike, as she would need to do, for example, with a bike with less powerful brakes.

Conceptualizing Complex Skilled Action

We now introduce some conceptualizations of complex skilled action that allow us to identify key features of Kath's experience at Croc's Teeth and illuminate the nature and role of the sense of agency.

Complex Causality

The kind of skilled action that Kath was engaged in exhibits complex causality and a

complex parametric structure. The outcome of braking, for example, is influenced by many factors, including features of the environment like surface topography (e.g., rough, smooth, steep, flat); surface type (e.g., loose sand, rock, slippery tree roots); equipment features (e.g., tire type, tire pressure, quality and condition of the brakes); and braking technique, dynamic shifts of body position to distribute weight evenly between front and rear tires, and in some cases drive weight down through the tires, providing better grip.

Control Interventions in Complex Processes

The processes involved in this kind of skilled action are temporally extended and show a high degree of continuity, rather than having a discrete action-outcome structure. Thus, applying pressure to the brakes typically serves as a control influence on an unfolding process such as adjusting speed to set up for an upcoming obstacle. In this kind of skill, action control often operates by adjusting one or more parameters in order to influence other parameters. We will call the first 'control parameters' and the second 'target parameters.' Applying pressure to the brakes influences a control parameter in order to change a target parameter—speed—which may itself be serving as a control parameter for another target parameter, such as a particular line around a corner. The distinction between control and target parameters is thus relative, illustrating the importance of prospective awareness in complex action sequences.

Causal Control Models

An ability to exert this kind of parametric control is based on what we call a *causal control model* that captures causal relations among performance parameters and allows the individual to flexibly and appropriately identify and influence control and target parameters in a particular situation. This allows the individual to achieve key performance goals, such as smooth riding and positioning for upcoming obstacles.

High Order Control

The kind of complex skilled actions described involve multiple levels of control. Kath adopted a particular strategic approach during

her initial ride down Croc's Teeth. She could have taken the section more quickly, trusting that the bike would perform well, but this strategy would increase the risk of crashing and, potentially, forfeiting the race. Instead, she adopted a cautious approach that involved riding relatively slowly and learning more about the bike and the trail. This strategy influenced her proximal control of the bike and her pattern of attention. As she gained information about the bike, she modified her strategic approach and her subsequent proximal control. Kath here was engaging in what we call *high order control*, which involves (a) sensitivity to the parametric structure of the performance situation, (b) use of this information for top-down adjustment of proximal control, and (c) appropriate adjustment of strategic control. Thus, information about the characteristics of the bike's suspension that she gained from feedback while riding had an immediate influence on Kath's proximal bike control, but also affected her strategy for later obstacles and overall riding approach. Her approach to the obstacle gave her room to alter her path or come to an early stop if performance went awry, which is what happened in the first attempt, and relied on an embodied ability to make on-the-fly adjustments to technique (Sutton et al., 2011; Christensen et al., in press).

Some Key Concepts for Understanding the Sense of Agency

The preceding concepts provide a starting point for understanding the kind of control involved in the type of complex skilled action described above. They also provide a basis for identifying key features of the SoA and its role in action control.

Parametric Causal Awareness

We define *parametric causal awareness* as awareness of key causal parameters that affect performance; for example, the compliance of the suspension, the stopping power of the brakes, the grip afforded by the tires and ground, speed, and distance to the corner ahead. Parametric causal awareness distinguishes contributions of the equipment and environment from personal contributions to an outcome, the awareness of which allows the rider to adjust her own control inputs as the parameters of the

environment and equipment change. An important component of the SoA is thus awareness of control acts in relation to the performance state, such as awareness that the current braking pressure is going to slow speed just enough to safely take a fast line around a corner.

To be clear, we are not claiming that the individual is aware of the full causal structure of performance. To clarify our position it will help to compare it with the common view that motor control is largely automatic. For example, according to this latter view, when reaching for a coffee cup you may consciously decide to reach, but the parametric details, including the specific trajectory, the speed of the movement, and the preparatory adjustments of the hand to grip the cup, are all determined by automatic processes (see, e.g., Frith et al., 2000, p. 1773). Accordingly, higher level action control generally consists in selecting coarsely specified actions, like 'pick up the cup,' leaving parametric details to automatic motor control processes. This view is held by Pacherie (2008), for instance. We do not deny that many automatic motor control processes occur outside awareness, but we reject the idea that people lack parametric awareness or control of actions at higher levels of control.

To appreciate why parametric awareness and control might be required at higher levels of action control it is helpful to consider the significance of the variability of key performance parameters. For example, if most of the parameters that affect braking in mountain biking were fixed or predictable, then they could be almost entirely ignored: a simple relation would exist between pressure on the brake levers and speed reduction, which could be learned by the predictive models described by Wolpert's internal models theory (Wolpert & Kawato, 1998). But the parameters that affect braking are highly variable, and a given amount of pressure on the brake levers could have widely varying outcomes.

Wolpert's theory explains context-sensitive adjustments of action in terms of the selection of contextually appropriate internal models based on perceptual cues. For example, different internal models might govern the action of picking up an object depending on whether it is perceived as heavy or light. But we doubt that this type of control is sufficiently flexible to fully cope with the variability of parameters that

influences actions like braking in mountain biking. The context-sensitivity provided by the internal models account is stereotypic, and it relies on stable, prelearned perceptual cues to trigger appropriate internal models.

In this respect it is useful to contrast the kind of models described by Wolpert's (Wolpert & Kawato, 1998) motor control theory with the causal control models we described earlier. Causal control models incorporate explicit representations of causal relations, whereas the predictive models of Wolpert's theory do not. Accordingly, causal control models are not dependent on prelearned perceptual cues, and this allows a situation-specific control model to be constructed based on the causal factors in the situation, facilitating effective control in new and idiosyncratic conditions. Causal control models are at least partly accessible to awareness and participate in high order control, which thereby affords responsivity to a wide range of information and allows for the rapid adjustment of control at multiple levels in response to variation in any causally significant parameter that is represented in the model. These characteristics allow for much greater flexibility of response than the internal models theory can account for.

One of the benefits of parametric causal awareness is that it supports flexible attention and diagnosis. For example, part way through a difficult rocky descent, a rider might find herself taking a poor line and moving too slowly. Her slow speed forces her to take a path around an obstacle rather than launching over it, because extra speed is needed to land safely on the other side. She may in turn realize that her disadvantageous situation during the descent is the result of overly cautious braking, or a poor line choice at the start of the descent. Thus, identifying the source of an immediate problem may involve tracing back from current performance state to control acts that are causally and temporally at a significant distance. Importantly, if individuals were *not* differentially aware of the contributions of their own control acts to performance state this kind of diagnosis would not be possible.

At any given point many of the causal relations that are or can be part of the causal control model will be in the background or outside of awareness, with attention focused on causal parameters that are immediately relevant to con-

trol. Once Kath became accustomed to the stopping power of the brakes on the new bike, for example, she no longer needed to focus on the brakes per se. Nevertheless, attention can flexibly shift to previously unattended causal relations as they become relevant.

Situation Awareness

Parametric causal awareness is part of *situation awareness*, which is an integrated holistic understanding of the situation as it relates to the control problems of performance (Endsley, 2006). Earlier we suggested that it is unlikely that the motor-outcome mappings involved in actions like braking in mountain biking can rely entirely on stereotypic internal models cued by perceptual features of the situation. Situation awareness, with integral parametric causal awareness, provides a layer of interpretation and adjustment, which means that control need not rely entirely on stereotypic models and prelearned perceptual cues, though such structures undoubtedly do contribute to control. Situation awareness informs the causal control model and provides the basis for high order control, which yields a fluid interplay between parameters of immediate control (e.g., a slippery tree root across the trail ahead) and strategic control, such as an approach to navigating the tree root. Good situation awareness is crucial to elite mountain biking, with competitors needing to adjust their approach in relation to a multitude of factors. For instance changes in the weather, deterioration of the track after many tires have passed over it, and fatigue can all greatly affect performance.

Prospective Sense of Agency

In our view the SoA also includes prospective awareness of potential control acts that can influence the performance state. When Wayne unclipped and put his foot down at the Ourimbah track, his subjective sense was that there was no action he could take that would allow him to keep riding. To avoid falling off he had to stop completely. Conversely, a positive prospective SoA involves awareness of the control acts that can achieve various desirable outcomes. If Wayne were able to pause and trackstand the bike, he may have been able to reposition his foot to provide a more powerful pedal

stroke—one that would see him accelerate over the rock without hitting his pedal on the way. Pausing earlier may alternatively have allowed him to readjust his line choice. Prospective SoA might include awareness of both possibilities and awareness that either outcome will be satisfactory.

Prospective Sense of Control

We also contend that the sense of control involves prospective awareness. To characterize this we employ the concept of a *performance envelope*, borrowed from aviation (Sinclair, 2005), which specifies the range of performance states that are possible or optimal. The performance envelope is readily illustrated for cornering: speed and line through a corner are interdependent, with higher speeds requiring a wider exit line, unless the rider can perform an advanced maneuver, such as flicking or drifting the wheels and altering the direction of the bike part way through. If the speed is too high, it may be impossible to get around the corner without running off the track or losing traction in an uncontrolled fashion. In our view the sense of control includes awareness of the relation of the performance state to the performance envelope. Control is secure when the current performance state is comfortably within the performance envelope, and is insecure near the edges. When Wayne feels insecure maneuvering at very low speeds, it is partly because it is harder for him to maintain balance; that is, he is near the edge of his performance envelope.³

Performance confidence can also involve a more generalized sense that the individual's action capabilities will be adequate for the challenges that the task is likely to present. Overall confidence will in turn affectively tinge the more immediate sense of agency involved in specific actions.

Reflective Strategic Awareness

Situation awareness incorporates reflective awareness of the significance of the immediate situation for the strategic approach to the performance and longer-term goals and strategies. Kath's strategy on her first ride down Croc's Teeth was in part shaped to her larger strategy for the race; by taking a cautious approach to

her first attempt at the obstacle she reduced the risk of a crash or equipment damage that would increase prerace stress and might lead to injury. As she gained confidence on the bike this danger was diminished, and she adjusted her riding strategy accordingly.

Reflective Epistemic Awareness

Highly skilled individuals can also have a finely tuned awareness of limitations in their situation awareness, including limitations in their senses of agency and control, in relation to the demands of the situation. This awareness can prompt adjustments in strategy and actions designed to enhance awareness. Kath's riding approach to Croc's Teeth exemplifies this process. The speed and line choice with which Kath entered Croc's Teeth on each attempt, for example, was not selected purely for moving over the first part of the obstacle, but for how it would influence her senses of agency and control for further riding.

Revisiting Croc's Teeth

We now combine these concepts to show how they illuminate Kath's first successful ride down Croc's Teeth. Reflective strategic awareness is one of the most salient features of Kath's experience. Kath realized that her limited understanding of the new bike could result in a crash, which might damage the bike and possibly injure herself, and which would affect her confidence and ability to compete in the race. Lack of familiarity with the bike and the track also meant that she did not have the information needed to ride the track at race pace. As Kath's understanding of the bike improved, she adjusted her strategy accordingly. Kath's reflective strategic awareness incorporated reflective epistemic awareness—she understood that she did not yet have the information she needed for good control, and her initial riding strategy revolved around acquiring this information.

One of Kath's initial aims was to 'get a feel for the bike.' In terms of the concepts we have

³ A further point to note is that the prospective senses of agency and control have a strong interdependence. What actions are available depends in part on the relation of the performance state to the performance envelope, and the relation of the performance state to the performance envelope depends in part on what actions are available.

presented, she was ‘parameterizing’ or calibrating her causal control model by discovering the parametric characteristics of the bike (e.g., brake stopping power, handling characteristics; see Figure 2). The calibration of Kath’s causal control model provided more developed prospective senses of agency and control; she had a much better sense of the performance envelope of the bike and what she could do riding it. This knowledge led to immediate adjustments in proximal and strategic control. She rode more aggressively and focused further ahead, approaching obstacles in ways that reflected the capacities of the bike and her own abilities on board. This fluid interplay between strategic and proximal control exemplifies high order control.

High order control continued to play a role in subsequent riding, but with changing objectives. Confidence in the bike, and her abilities

on board, allowed Kath to focus on other elements of the performance process. When she returned to Croc’s Teeth a second time, almost 24 hours later, the risks stemming from a lack of familiarity with the bike and the terrain were reduced, and her focus shifted to riding a smoother, straighter line through the obstacle. She was now preparing to race the same track the next day, pushing her skillset, encompassing what she now knew about the capabilities of the bike, at a faster speed. With limited time available for practice she was not aiming at perfection, but recalibrating a skilled repertoire to a specific bike and trail in a way that was ‘good enough’ for traversing it at a higher speed during the race itself.⁴

It bears emphasis that the flexibility of high order control will give rise to substantial variability among individuals. Factors such as personality, attitude, and emotion influence actions and attentional focus (McIlwain, 2006). Thus, other riders may have approached a situation like Croc’s Teeth in a manner very different from the approach that Kath adopted (e.g., faster initial speed, or greater concern with identifying an optimal race line).

The Relation Between Skill and the Sense of Agency

One of the key issues that our account addresses is the contribution of the SoA to action control. Specifically, we contend that the SoA and sense of control contribute to high order control, which provides flexibility—the ability to adapt rapidly to complex situations, fluidly adjusting proximal and strategic control—that is required for complex skills like mountain biking. High order control provides a starting point for addressing the basic question we began with, namely the relation between skill and sense of agency. Because the SoA contributes positively to skilled action control, we can reasonably expect that skill learning will enhance SoA for the kinds of actions performed as part of the skill.



Figure 2. Attacking Croc’s Teeth during the second day of the race. Kath’s body position is more aggressive. Her weight is further forward over the front wheel and her focus is fixed firmly ahead. Extra protective gear is worn in anticipation of more difficult trails ahead. Photo: Reilly Hurst.

⁴ For further discussion of the phenomenological process of incorporating new skills into an embodied action schema, see Bicknell (2010). For examples of rapid adjustment to an action plan during competition (in response to spectator encouragement), see Bicknell (2011).

One of the most basic ways that skill learning will enhance the sense of agency is through improved sensitivity to key parameters. Based on Kath's instructions and feedback, and Wayne's interpretation of his experiences, Wayne's ride at Ourimbah left him with a much clearer realization of the importance of low-speed bike control and a better understanding of the importance of balance, pedal placement, line choice, and entry speed in such circumstances. In subsequent riding he has attempted to improve his awareness of these parameters. Improved parametric awareness should in turn help in constructing causal control models and the awareness of the contingencies of the performance envelope. Among other benefits, increased awareness will improve the localization of sources of success and error, which will improve the focus of subsequent learning (Christensen & Hooker, 2000).

An important question, however, is whether high order control continues to play a critical role at the most advanced skill levels. According to influential theories of skill learning, control becomes largely automatic in the final stages of skill acquisition (Fitts & Posner, 1967; Dreyfus & Dreyfus, 1986). In our view this is not generally the case (Christensen et al., in press), and reports from elite athletes reveal the kind of multifactorial, higher order, reflective awareness that we have described in Kath's experience (see also Bicknell, 2013). Indeed, the parametric awareness of performers at the highest levels can be remarkably precise. After his seeding run for the 2013 UCI Downhill Mountain Bike World Championships,⁵ Jared Graves increased his front and rear tire pressure by 1 psi "as they were still a bit squirmy on a couple very high speed G-outs."⁶ This would make his tires handle the transition in and out of these trail features in a more controlled fashion—the casing on his tires would deform less (reducing the squirming sensation), thereby decreasing the probability of a puncture. This adjustment involves his observing equipment function *during* the practice run, on more than one obstacle, and in *anticipation* of the track conditions and speed he would carry in his competition run (Graves, 2013). Graves went on to win the bronze medal. Rosemary Barnes, the series winner of the Elite Women's Australian Gravity Enduro Mountain Bike Series, reported choosing a (more protective) full-face

helmet for a recent Gravity Enduro race because of its influence on her emotional state (Rocky Trail Entertainment, 2014). Rebecca Henderson (2013) reports on a race in which hunger, mechanical problems, crashes, and fatigue from a long race season consistently disrupts her performance plan. She observes the positions of her competitors and knows that one particular girl is likely to finish in second place, which means that Henderson needs to finish fourth or higher to secure the overall UCI Under 23 Cross-Country Mountain Bike World Cup series title. Henderson finds opportunities to take additional drink and a caffeinated energy gel, she adapts her riding style to descend through a rock garden with a flat rear tire, notes when she has taken a bad line and is headed for a serious crash, and draws on high levels of motivation to overcome pain. She succeeded in finishing fourth, and consequently won the title. This performance shows considerable awareness, flexibility, adjustment, and emotion control.

A further question is whether substantial differences in high-order control and SoA are evident across diverse elite and everyday skills. Our expectation is that numerous specific differences will be apparent, but the core structure of high-order control will, nevertheless, be present in most skills. Montero (2010) argues that in elite skills individuals typically strive for continual improvement, and they may need to innovate to succeed in high stakes performances. Conversely, she suggests that in the case of artistic skills, rote performances are dull and tend toward stereotypes. She also points out that attention is needed for online corrections. We agree with all these points, and further suggest that nonstereotypic performance can be vital even for nonartistic skills because it allows fine-grained sensitivity to situational nuances. However, we also believe that parametric awareness and high-order control are important in everyday skills. Even the skill of walking involves surprisingly rich and subtle parametric sensitiv-

⁵ UCI stands for "Union Cycliste Internationale." This organization is the international governing body for cycling.

⁶ By G-out, or gravity-out, Graves is referring to the impact of gravity on motion during changes of direction, such as during very fast transitions from a downward slope to a flat road or upward slope. Trail features that have this effect are described as G-outs because of the way they are experienced when ridden.

ities to the shape or texture of the surface we are walking on, obstacles in our path, or the properties of the shoes we are wearing.

Relation of Our Account to Pacherie's Theory

These case studies, and our conceptualization of them, are supportive of and build on some of the key features of Pacherie's hierarchical model of the SoA. In particular, our account reinforces the importance of multilevel control for understanding the SoA, and supports Pacherie's conception of multilevel control as involving rational (which we call strategic) situational and motor control. Nevertheless, we depart from Pacherie in some of the ways that we characterize the SoA and the sense of control.

A basic feature of Pacherie's account is that it addresses occurrent SoA, which is understood as distinct from long-term SoA. More specifically, she aims to explain immersed, nonreflective SoA. According to our account, however, occurrent SoA incorporates multiple kinds of reflective awareness, including reflective strategic and epistemic awareness. The prospective senses of agency and control also incorporate reflectivity in terms of evaluation of current performance state. Moreover, one of the functions of reflective strategic awareness is to integrate long-term with immediate agency. Another key difference between Pacherie's account and ours is that Pacherie uses the comparator model to explain the sense of control. However, comparator processes cannot explain the prospective sense of control, which must involve more complex forms of predictive evaluation.

According to Pacherie's account, 'how-awareness' consists of awareness of the means of performance at each level of control. Broadly interpreted this should incorporate the parametric causal awareness we have described, but Pacherie's account does not recognize this kind of awareness explicitly. Our emphasis on the role of causal representation in the sense of agency has notable similarities to Wegner's (2002) approach, but unlike Wegner we do not believe that the SoA is systematically misleading. On the contrary, we contend that it is often accurate, and that complex skilled action depends on this accuracy. Other recent research has also linked the sense of agency to causal

representation, including Buehner (2015) and Desantis et al. (2011).

Pacherie also claims that there is little parametric awareness of motor control, but as we argued earlier, we believe this is incorrect. Motor acts that are calibrated precisely in relation to complex situations are essential for skilled sensorimotor control—a mountain bike rider needs to exert *just enough* brake pressure to wash off enough speed to make the corner without slowing too much. We have claimed that this calibration is at least partly performed by high order control.

Pacherie's view that the SoA involves little motor awareness is in keeping with the general belief that motor control is automatic, but she also appeals to experiments by Fournerey and Jeannerod (1998). In these experiments participants moved a stylus on a tablet to draw a line to a target. They were seated and looked toward the tablet and their hand, but a mirror was positioned above their arm which prevented them from seeing their arm movements. A computer-generated display projected onto the mirror showed the line being drawn and the target. On some trials perturbations were introduced so that the hand had to move at a divergent angle to draw a straight line to the target. The key finding was that participants were unaware of such divergences unless the discrepancy was quite large.

Nevertheless, we do not believe that findings from this experiment warrant the conclusion that motor awareness is generally poor. Consistent with cue integration theory (Synofzik et al., 2008; Moore & Fletcher, 2012), we expect that motor awareness flexibly exploits diverse kinds of perceptual information, including visual information. In many kinds of manipulation tasks, including normal drawing, visual perception is a rich source of information concerning hand and arm movements. Participants were deprived of this information, making the task quite unusual.⁷ They also were not provided with feedback regarding discrepancies. With the provision of such feedback and extended practice, they might learn to detect the perturbations. For comparison, Wayne currently has relatively poor balance awareness in

⁷ See Christensen et al. (2015) and Christensen et al. (in press) for discussion of problems with drawing general conclusions about action control on the basis of ecologically unrealistic tasks.

bike control, which manifests in poor balance at low speed and difficulty trackstanding, because poor body positioning results in instability. However, the feedback acquired through practice is helping Wayne improve his balance awareness. Bodily awareness is structured by the demands of control and can change and develop through learning.

Conclusion

Our overarching concern in this article has been with developing an understanding of the SoA that clarifies its nature and role in complex real-world actions. We claim that it is important that theories of action and the SoA be informed by detailed evidence concerning the phenomena as they occur in the real world. We have drawn on a brief comparison between Kath and Wayne's differing approaches to an uphill, rocky corner, together with a more detailed description of Kath's experiences at a high-level mountain bike competition, as a starting point for investigation. These experiences and approaches suggest differences in capacity for prospective awareness between an expert and a novice rider, and provide insights into the performance processes exhibited by an expert rider adapting to novel circumstances.

Our account requires further validation, and two strands of investigation stand out as particularly important. The first is systematic cognitive ethnographic research, which would examine the SoA among a broad range of experts at different skill levels in varied circumstances. The second is experimental investigation of awareness of the parameters of actions that have complex causal structure, and the role that such sensitivity may play in action control. We suggest that parametric awareness should develop in tandem with increasing skill level.

Finally, our account has implications for practical interventions to improve action control and decision-making. We suggest that training methods that enhance parametric sensitivity and prospective action awareness may improve the capacity to adjust to complex situations, engage in on-the-fly strategic decision-making, and trouble-shoot problems. This perspective might offer fresh insights and approaches to action in skill domains that seem, at first, like they have

very little to do with rock gardens, crocodile teeth, or helping a friend to reach the top of a hill.

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- Received January 14, 2015
Revision received June 16, 2015
Accepted June 22, 2015 ■