Consciousness without inner models?
A sensorimotor account of what *is* going on in our heads

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Extended abstracts

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Introduction

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There has been much criticism over the years of the idea that conscious experience depends on inner representational models of the environment. Enactive accounts and the sensorimotor account more particularly [1,2] have criticized the reliance on inner models and they have offered an alternative way of thinking about experience. The idea of sensorimotor approaches is that experience involves the perceiver's attunement to the way in which sensory stimulation depends on action. But how then should we conceive of what happens in the agent's head to allow for this attunement? The main aim of this symposium is to address this question, focussing on the following two questions. First, how does an enactive sensorimotor theory offer guidance for the interpretation of neurophysiological findings? Second, how are its predictions about neural processes different from the predictions of representationalist accounts?

The first question, concerning the philosophical interpretation of neurophysiological findings, may be addressed by focusing on key processes such as corollary discharge or 'efference copy' and notions like 'expectation error' and 'forward models' in relation to the sensorimotor account or enactive accounts more generally. Here the main question is how to get the brain into view from an enactive/sensorimotor perspective. Where classical approaches speak of neural computation of properties of the environment, or the build-up of representations in the brain, what specific analysis can a sensorimotor account offer in its place? Addressing this question is urgently needed, for there seem to be no accepted alternatives to representational interpretations of the inner processes. Also robotic models of perceptual processes are often interpreted as mimicking the allegedly representational nature of neural processes. A sensorimotor account could help to avoid this bias towards interpretations based on the notion of inner models.

The second question, concerning the predictions following from an enactive/sensorimotor account, requires contrasting the neural processes that are postulated in representational theories, with the processes required by the enactive/sensorimotor account. Which processes postulated by representational accounts are rejected by the sensorimotor account or enactive accounts more generally? For example, why and when can neural 'binding' or 'filling in' be rejected? And are there processes that are specifically required by sensorimotor theory, which are not required by representational theories? In the symposium we aim to clarify which constraints on inner processes are proposed by the sensorimotor account. If the sensorimotor account is right, these constraints will of course apply to neural processes as well as to robotic models of perception.

In addition to spelling out nonrepresentational interpretations, the symposium will discuss the possibility for representational accounts of sensorimotor engagement, as in the invited contribution of Anil Seth on a predictive processing interpretation. An evolutionary perspective on sensorimotor organization is represented by the invited contribution of Fred Keijzer. Together, we think the extended abstracts give a good impression of the cutting-edge work that's being done on the neuroscience of sensorimotor interaction.

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What is the brain doing in the sensorimotor theory?

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Abstract. The sensorimotor theory considers experience to be a thing we do, claiming that experiencing, say, redness, consists in currently exercising mastery of a sensorimotor engagement with something red. Under this view, the quality of a particular experience is constituted by those laws that govern the interaction underlying that experience. We emphasize that this de-reification of experience appeals to *potential* action and its sensory consequences, pointing out that exercising mastery of sensorimotor contingencies does not require present action. What is the brain doing when we are exercising this mastery? How does the brain relate to the multiplicity of possibilities linking possible actions to resulting sensory changes? We reject the view that these sensorimotor contingencies are explicitly represented in the brain: all that is necessary is that there exist mechanisms in the brain able to test their presence. We suggest that as observers become acquainted with sensorimotor contingencies, fewer neural resources are necessary to group together the multiple counterfactual sensorimotor contingencies associated with a given experience.

1 BRIEF INTRODUCTION TO THE SENSORIMOTOR THEORY

The idea that experience must necessarily be generated by the brain has led to decades of research on neural correlates of consciousness, with a variety of hypotheses (ranging from recurrent cortico-thalamic oscillations to quantum gravity effects in microtubules!) failing to make progress in explaining the phenomenal quality of experience.

As a remedy, the sensorimotor theory starts anew on the issue of experience, proposing that there is a category mistake involved in thinking that experience is the kind of thing that can be generated by anything, let alone by brains. Instead the sensorimotor theory suggests that we should consider experience to be a thing we do, like a skill [1]. For example, a bodily skill like skiing is not "generated" in the brain, but rather, it consists of a certain ongoing interaction with the environment. The sensorimotor theory extends this idea to sensory experiences, claiming that the experience of say red, is constituted by our bodily, sensory engagement with red things.

Under this view, the quality of a particular experience is constituted by those particular laws that govern the interaction underlying that experience. So for example the quality of softness of a sponge is constituted by the fact that when you press it, it squishes.

The wager of the sensorimotor theory is that de-reifying experience in this way is a tactic which will be as successful as was the de-reification of the notion of "life" at the beginning of the 20th Century, a tactic which led to abandoning the idea of vital spirit and to the birth of modern biology.

2 NOT ACTION, BUT POTENTIAL ACTION

A key notion in the sensorimotor theory is action. As is the case in the execution of any skill, the theory claims that there can be no experience without the perceiver's activity. However it is important to understand that the perceiver need not act now. Just as the jeweller is immobile as he solders the ring, just as the dancer pauses an instant in his dance, having an experience implies being in the process of masterful sensorimotor engagement. But "having mastery of sensorimotor contingencies" does not require action at this very moment. Rather, it involves having implicit knowledge or mastery of a variety of currently possible actions and their consequent effects on sensory input. Experiencing involves being "tuned" to the possible changes in sensory input, in the sense that one is in a state where one knows implicitly that if one makes this action, this change in sensory input will occur, and if one makes that action, that change will occur.

The fact of appealing to potential action and (counterfactual) sensorimotor contingencies allows the theory to account for perception without action, but also for dreaming, imagining, hallucinations and even synaesthesia. By further appealing to the notions of "bodiliness", "insubordinateness" and "grabbiness", the theory can also account not only for the sensory quality, but also for the degree of experienced perceptual presence of such experiences (e.g. [2]; [3]).

3 THE MEANING OF MASTERY

What is the brain doing when we are exercising mastery of sensorimotor contingencies? How does the brain relate to the multiplicity of possibilities according to which if we do this, then that will happen? Does it have a large list of all the possible things we can do, and all the possible expected sensory consequences?

This would be at best un-parsimonious and at worst impossible, given that there are probably an infinity of possibilities. An alternative is to assume that the brain has a shortcut way of determining whether a particular law (or invariant) is applicable, allowing the current sensorimotor contingencies to be grouped together in this or that experience.

To illustrate, take the case of colour. A sensorimotor approach to the experience of colour has been proposed recently by [4], and provides an appealing account of classical phenomena about colour naming and unique hues. According to this, experiencing colour consists in currently engaging with the changes in retinal photoreceptor excitations that will occur when you move a coloured surface around under different illuminations. Thus for example, the light reflected off a red surface will change drastically when you move the surface from

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a white room to a blue room: and despite this the surface continues to appear red. To identify a surface as red however, the brain need not predict each such change. Instead, it can simply determine if a particular relationship holds between the sensory stimulation from the illuminant and the sensory stimulation from the surface. The work shows that this relationship can be accurately represented by a 3 x 3 matrix, distinct for each colour.

Thus seeing red does not consist in predicting at every moment what precise changes will occur in sensory input -- but in the fact that the changes that occur are compatible with the matrix corresponding to red. And more generally in all sensory experiences, the sensorimotor theory proposes that the multiple (counterfactual) possibilities inherent in implicit knowledge of sensorimotor contingencies will not each be precisely instantiated in the brain. Rather, a much more economic neural process will exist which allows ongoing sensorimotor contingencies to be grouped together within particular percepts without anticipating the exact sensory states expected for each possible action. Gilbert Ryle expresses a similar idea in describing what happens when one is perceiving a thimble: "Knowing how thimbles look, he is ready to anticipate, though he need not actually anticipate, how it will look, if he approaches it, or moves away from it..." [5]. In other words there is no real anticipation in the sense of recreation of the expected stimulus. There is just confirmation that the law applies.

Perhaps a link may be made here to hierarchical predictive coding theories, where the 'predictions' being made are not of actual sensory inputs, but of higher-level, and thus more economic, neural activity (cf. [6]). Another link to be made with current brain theories is the following. The sensorimotor theory suggests that as observers become acquainted with the sensorimotor contingencies involved in a sensation, fewer neural resources will be necessary to group together the multiple counterfactual sensorimotor contingencies which are associated with that skill. The reason is that by adapting to a sensorimotor invariant you become relatively insensitive to the variations. This is reminiscent of the finding that skill acquisition decreases the activity in various parts of the brain during performance of a task (e.g. [7]).

4 A FINAL NOTE: ARE SENSORIMOTOR CONTIGENCIES REPRESENTED IN THE BRAIN?

Just as the sensorimotor theory rejects the idea that experience is generated in the brain, the sensorimotor theory also rejects idea that perception involves activation of internal representations. Experiencing the world does not involve having pictures or descriptions in our brains -- it involves interacting with the world in a masterful fashion. Experiencing should be de-reified like life has been de-reified. Experiencing is a particular way of interacting with the world.

Yet it could be objected that in order to interact with the world in a masterful fashion, there must be "something going on in the brain" that allows this mastery, and that this something represents the sensorimotor contingencies. For example, the matrix corresponding to red must be stored in the brain in some way, and when this storage is activated, we see red. Surely then, seeing red is "activation" of the representation of matrix A!

BUT NO: seeing red involves activation of the neural processes enabling the interaction that is described by the matrix for red. But the neural processes do not themselves describe the matrix, or contain the phenomenal quality of experience. The experience of red lies in what you do when you are interacting in the appropriate way.

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To be a proper non-representational theory of perception, the sensorimotor approach must be a fully non-representational theory of behaviour

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Abstract. The sensorimotor theory of perception claims to be nonrepresentational. However, when dealing with some aspects of perception, such as epistemic properties, the theory retains conceptual aspects that are germane to representational accounts. In order to depart definitively from representationalism, it is suggested that the sensorimotor theory must treat perception as a behavioral process first and foremost. When treated thus, one of the main questions regarding perception is that of anticipation. Forwards models, which are presently very popular, constitute representational explanantia to anticipation. A different way to explain anticipatory behavior is proposed. Based on an analogy with bodily dispositions to act such as postures, it suggested that the task of the brain might be to bring itself and the body into hierarchically nested states of readiness to action towards perceived stimuli. Perceptual knowledge consists not in prediction of sensory changes but in nonrepresentational cognitive postures.

The version of the sensorimotor approach (henceforth SMT) that was introduced by O'Regan and Noë [1] is highly compatible with other approaches to perception which rely on predictions of sensory stimulation (e.g. the popular active inference approach [2, 3]. Yet sensory predictions are still representations and they can still be associated with the presence of complex world models in the cognitive apparatus [4]. Having concentrated mostly on problems of visual conscious experience, the SMT shunned one kind of representationalism that not many authors actually defend viz. pictorial representations [5]. The brain may not construe a detailed pictorial representation from current experience but may still have a previous ("prior") rich and abstract world model which it tests against the actual world.

In order to depart from these heavily representational theories, the authors of SMT must first understand that their opposition to inner models in general takes place on a behavioral ground. Efference copy, for instance, is posited as a solution to behavioral problems [6, 7, 8]. Thus, SMT should be a fully non-representational theory of behavior rather than of conscious experience. It must hypothesize or discover non-representational sensorimotor mechanisms that generate complex behavior which would normally be explained by appeal to representational knowledge (e.g. the "representation-hungry" cases [9, 10].

An example of such non-representational neural mechanism with its corresponding non-representational interpretation can be found in recent work on preparatory activity in the motor cortex ([11]; [12]; [13]). The traditional representational view of motor and premotor cortices function is that neurons therein encode final specific features of movement and/or of movement activity (e.g. speed, torque, etc.). An alternative hypothesis which seems to be vindicated by empirical findings is that individual neurons operate mechanically, setting up initial conditions for the dynamic unfolding of downstream neuromuscular activity.

If SMT opts for the non-representational path it must urgently unpack representation-loaded concepts present in its explanatory framework in a non-representational way. One such problematic concept is that of "knowledge of potentialities" ([1], p. 949). Noë [14] argued that it is a kind of conceptual knowledge, which raised worry from Keijzer [15]. Indeed it seems rather counterproductive to hold that perception requires conceptual knowledge while insisting on the fact that it is a practical knowledge ([1], p. 944). The problem could be avoided, once again, by insisting on the fact that SMT ought to explain behavior first and foremost, while Noë's position seems respond to a need to explain epistemic features of perceptual phenomena. In contrast, forward models, as non-conceptual knowledge, are put forward in an endeavor to account for anticipatory features of behavior. How, for instance, does the brain compute the right trajectory of, say, an arm when it can't count on sensory feedback for adjustment? Knowledge of potentialities in the SMT should thus serve the same purpose of explaining anticipatory features of behavior. What was expected from SMT, then, was non-representational anticipatory mechanisms for complex behavior [16, 15], instead of "knowledge" and "concepts" which are already present in more classical theories.

I suggest that a way to obtain the desired mechanisms in a sensorimotor account could consist in replacing anticipation of sensory input with some process akin to preparatory posture adjustment [17]. A baseball player, for instance, prepares the body to catch a ball before moving his arms towards the intercepting point. The preparatory posture is anticipatory yet doesn't represent the ball trajectory, nor the laws of physics governing it (as opposed to [18])--at least not in a non-trivial way. By extension, the (mature) neuromuscular system too could be conceived of as assuming postures by poising itself into an anticipatory yet non-representational state, where further incoming stimuli will be responded to in an adapted way. As an illustration, when I see a red tomato, my humanly trained brain poises itself into a behavioral state of readiness to all sorts of different actions modulated by my homeostatic state, context, etc., like my bodily posture. This state could be achieved by tuning the initial states and relevant parameters of the dynamic attractor landscape embodied in the neuromuscular system that was discovered by learning to successfully deal with red tomatoes [19, 20]. Notice, to intercept a widespread objection, that behavior need not be triggered by this state, not even covertly.

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The concept of neuromuscular anticipatory posture can be nicely linked to Gibson's affordances, since the state of readiness to act corresponds to the concept of "opportunity for action" [21] Thanks to its being behavior-oriented, the concept can also provide a more natural meaning to the non-representational practical "knowledge" the authors of SMT are striving to explicate. Moreover, three critical properties typically ascribed to representational processes can be obtained with postures, viz. instantiation in absentia of stimuli, continuous sequences of internal state changes, and complex internal structure [22]. Indeed the neuromuscular system can (1) enter a poised state of readiness for action in the absence of its normal triggering stimulus, (2) follow sequences of changes from one poised state to the next in the absence of changing stimulation or, crucially, anticipating it temporally [23], and (3) support complex structure such as hierarchical organization where some region of the brain enters a state of readiness vis-à-vis another region of the brain. Finally, preparatory posture could, although as an incidental effect, explain what a perceptual state is: the system poised in the behavioral readiness towards the input, not by predicting how the input could change but by being ready to change itself towards the particular behaviors the input can trigger.

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Bilateral mutual gain control, beamforming, and Being There

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Abstract. In this presentation we will discuss our recent work on beamforming as a mechanism of selective attention, and its potential relationship to the enactive agenda. We propose that the enactive approach would benefit from extension to incorporate array sensing concepts and formalisms, and that array sensing expresses certain enactive core concepts in a practical way. Perception is radically embodied in that the physical morphology and dynamical distribution of the sensor array is fundamental. Attentional presence is extensive in physical spacetime in a quantifiable way, and is not reflected by any internal models. Beamforming with multimodal and dynamically adaptable array morphology is a state-of-the-art problem in communications technology. Thus the study of perceptual actions in animals as modes of beamforming may offer valuable mutual interaction with formal theory.

1 BILATERAL MUTUAL GAIN CONTROL AND BEAMFORMING

A. Bilateral mutual gain control and sensory attentional gating

The bilateral structure of the brain and body is aligned and integrated according to symmetric correspondence at many stages of sensory and motor processing. Mutual gain control (henceforth "MGC") is the most plausible general framework for bilateral sensory interaction, though many particulars exist at a more detailed level [4, 29, 10, 10, 28, 21]. From an aesthetic perspective, the "sweet spot" region of binaural synchrony is manipulated by sound engineers to deliver the most enjoyable and engaging listening experience [24, 2], suggestive of a more general multimodal link between bilateral gain control, arousal and "liking". Gain control is widely thought to mediate selective attention [8, 18, 1, 16, 17, 6, 20], and has been mechanistically linked to ascending projections from neuromodulatory hubs and the sympathetic nervous system [25, 1, 19], as well as feedforward mechanisms such as temporal correlation of presynaptic potentials [14].

B. Beamforming, orienting and motor attention

Beamforming is a technique for manipulating the spatial tuning of a sensor array [15]. The mathematical essence of beamforming is maximisation of constructive interference between the signals from an array of sensors. Integrating the signals from the array creates a set of preferred source locations for incoming signals. MGC is one possible integration function e.g. [11]. When the signals from all the sensors are temporally aligned, constructive interference is maximised and the input signal is faithfully reproduced. Otherwise, destructive interference damps the overall power of the signal. Adding differential delays to the sensor inputs, or physically turning the array, can rotate this "attentional beam" in space, so that sources at particular locations (e.g. a mobile phone) can be targeted, whilst noise from elsewhere is tuned out; a kind of technological "selective attention". Physically turning the array is analogous to the psychological concept of orienting or overt attention. Adding delays to "virtually" orient the array is analogous to "covert attention". Overt and covert attention are thought to be tightly linked [5, 3], though appear to be mediated by different cellular networks [7].

2 BEAMFORMING AND BEING THERE

A. Attentional presence, embedded in spacetime

Beamforming projects an attentional field onto physical spacetime, which it is convenient to view in terms of "virtual sensors" extended into the environment. The visual horopter provides an example of one such virtual sensor, [22, 23], the auditory midline another [12]. The neural transforms (minimally, pointwise multiplication of the stereo signals) required are quite the opposite of internally representing space; (i) they purely collapse the spatial and modal extent of the array, (ii) they only discard and compress sensory information, (iii) they can be purely local and spatially uniform.

Spacetime is selectively inhabited externally by being selectively collapsed internally. Inhabited here refers to the tuning of the sensor array to particular locations and patterns of signal sources in the world, regardless of the signal content. This tuning is effected by the dynamic global posture of the sensor array at both the musculoskeletal (overt attention) and neural (covert attention) level. It is most convenient to characterise the agent's "presence" as an attentional field probabilistically co-extensive with the spatiotemporal lines of sight (or hearing etc) of its sensors. Indeed, there is no obvious alternative. It is not possible to properly characterise the form of the attentional field in terms of, for example, the retinal projection.

B. Context, content and consciousness

Hutto and Myin [9] argue for the possibility of consciousness without content. Beamforming provides a well worked formalism for defining attentional presence, regardless of content. Active maximisation of constructive interference (i.e. spatiotemporal resonance between sensor array and scene) corresponds fairly directly to Merleau-Ponty's notion of perception through establishment of "maximal grip" on the scene [13]. The content of the signals may be discarded as soon as this

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quantity has been calculated. The array sensing approach is not anti-content, though. Indeed, it may play the role of framing and selecting content, and for this reason we associate beamforming with providing the spatiotemporal context of perception.

It is possible to make perceptual distinctions purely on the basis of beamforming. We have already shown that a number of "innate predispositions" regarding spatial-configural perception and social attention in newborns may be explained by bilateral MGC [27, 26]. Consider a sensory substitution device with one or more bilateral sensor pairs, whose signals are integrated by MGC. It outputs a one dimensional signal corresponding to the global level of constructive interference between all the bilateral sensor pairs. What perceptual distinctions are possible for humans and robots given some control of the array and this minimal feedback, and how are they made? Overall, we argue that array sensing provides a well specified and under-exploited paradigm to both explore and exemplify the potential of enactive perception.

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The role of sensorimotor feedback in a brain state transition from passive to active processing

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Abstract. Both the sensorimotor and enactivist accounts have successfully emphasised the centrality of sensorimotor feedback for accounts of cognition. Despite this success the migration of this focus to mainstream systems neuroscience has been slow. Recent experimental innovations mean that this state of affairs is beginning to radically change. Closed-loop experimental paradigms that utilise virtual reality in mice and fish and well circumscribed sensory-motor systems are becoming more widespread. Consequently, in vivo electrophysiology and optogenetics of behaving animals is quickly becoming an achievable gold standard. This work places the sensorimotor loop at the heart of neural processing and promises to give sensorimotor accounts renewed relevance for mainstream neuroscience. Here we utilise these technologies to examine the role of sensorimotor feedback for accounts of neural dynamics and brain function.

Sensory perception and motor action are inseparably bound by reafferent sensorimotor feedback (sensory input resulting from an animal’s own actions) mediated by the body and environment [1]. Both the sensorimotor and enactivist accounts have successfully emphasized this aspect of cognition to mount a systematic challenge to some of the dominating concepts in the cognitive sciences [2, 3]. Despite this success the migration of these ideas to mainstream systems neuroscience has been slow. However I would argue this does not amount to conceptual resistance to the role sensorimotor feedback but, at least in part, reflects experimental practices which are dominated by heavily restrained, or anaesthetised animals, where body/environment feedback is minimised. Recent experimental innovations mean that this state of affairs is beginning to radically change. Closedloop experimental paradigms that utilise virtual reality in mice and fish [4,5] and well circumscribed sensorimotor systems are becoming more widespread [6]. Consequently, in vivo electrophysiology and optogenetics of behaving animals is quickly becoming an achievable gold standard. This work places the sensorimotor loop at the heart of neural processing and promises to give enactivist and sensorimotor accounts renewed relevance for mainstream neuroscience. Here we utilise these technologies to examine the role of sensorimotor feedback for accounts of neural dynamics and brain function.

It has been understood for a long time in the neurosciences that engaging world, and thus engaging sensorimotor (or reafferent) feedback, can have a profound effect on brain state (a pattern of brain activity and responses)[7]. Transitioning from a passive to an actively engaged state suppresses both neural fluctuations and intraneural correlations, e.g. opening one's eyes [7] or the onset of whisking in rodents [8]. Furthermore, the onset of active behaviour strongly modulates sensory processing [9,10,11]. Typically the sensitivity of neurons to perturbation is larger in passive rather than active states [10] however robust response in the active state are recovered for biologically relevant sensory events [10,12]. The trigger for this brain state transition has been subject of several recent studies [10,8,13].

Most investigations have focussed on describing centrally generated mechanisms. It is likely that multiple internal factors are involved in brains state transitions [13,14,15]. However here we describe a simple theory that can account for all brain state phenomenology by appealing to the role of sensorimotor feedback. Specifically we hypothesise that when an animal engages the world its body and environment mediate negative feedback to the brain. We show that this negative sensorimotor feedback can suppress brain dynamics and thus account for the reduction of intraneural correlations, fluctuations and response to perturbation associated with the onset of a brain state transition. In effect we suggest the body and environment stabilises the brain. We ground this idea in the rodent whisker system and provide experimental evidence by describing work on zebrafish larvae behaving in a virtual reality environment.

We show how this hypothesis suggests a new sensory mechanism that can explain active sensing in the rodent whisker system. Specifically in the rodent barrel cortex response are large in a passive nonwhisking condition but are suppressed during active whisking [10]. However large responses are recovered during active whisking for more natural touch events, i.e., when the whisker collides, and temporarily remains in contact with, an external object [10]. Our theory can account for this phenomenon by idealising these touch events as brief interruptions of negative sensorimotor feedback which temporarily destabilise the cortex and thus evoke large responses in the active condition . The implication of this mechanism is that animals are particularly sensitive to the interruption of their own sensorimotor feedback rather than just external (exafferent) input. This mechanism has strong similarities to, and indeed we regard it as a special implementation of, the principle of reafference [1] (or more broadly predictive coding). However there are strong functional differences thus we compare and contrast both mechanisms.

Lastly, there is a strong current trend in neuroscience to stress the importance of using naturalistic, e.g natural movies, rather than artificial stimuli in order to faithfully characterise the response properties of different sensory modalities. However our theory predicts that even if the input from a closed-loop active behaviour is recorded and exactly replayed, at a later time, to an identical but passive brain, the brain dynamics between the two conditions will still be qualitatively different. In effect our theory suggest that neural function is strongly contingent on presence or absence of sensorimotor feedback. We confirm this prediction by studying neural activity in larval zebrafish behaving in a virtual reality environment [5] and comparing brain dynamics between a closed virtual reality and passive replay condition.

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Structural affordances & the embodiment of bodily experience

Adrian Alsmith[1]

Abstract. A psychological phenomenon is strongly embodied if it can only be adequately explained by giving a distinctive explanatory role to the body itself; it is weakly embodied if it can only be adequately explained by giving a distinctive explanatory role to representations of the body. My aim is to show that any tension here is superficial. One can hold a strongly embodied view that nevertheless admits the presence of mental representations of the body in the cognitive system. I illustrate one such view, by showing how the notion of a structural affordance, an affordance relation that holds between an agent and its actual body, can play an explanatory role in any account of bodily experience that admits that parts of the body may be represented without a system representing the body as a whole.

Embodiment means many things to many people. Two ways of thinking about explaining the nature of a mental phenomenon by appeal to its embodiment are in prima facie tension with one another. For some, a psychological phenomenon is embodied if one can only adequately explain that phenomenon by giving a distinctive explanatory role to the body itself. Call this strong embodiment. For others, a psychological phenomenon may be embodied without there being a distinctive explanatory role for the body in its explanation; it may be embodied only in so far as there is a distinctive explanatory role for representations of the body. Call this weak embodiment.

The suggested tension here is between the representationalist account suggested by weakly embodied views and the non-representationalist account suggested by strongly embodied views. My aim is to show that, in this instance at least, that tension is superficial. One can hold a strongly embodied view that nevertheless admits the presence of mental representations of the body in the cognitive system. In particular, I aim to demonstrate the coherence of such a view on the embodiment of bodily experience. Even if one is committed to there being some degree of mental representation of the body enabling the phenomena of bodily experience, it may nevertheless the case that such bodily experience is strongly embodied.

A key part of my argument turns on the fact that agents stand in a certain kind of affordance relation to their own bodies, a relation of structural affordance. Structural affordances can be most simply explained by comparison with more familiar agent-environmental affordance relations, such as where an agent sees a tree as climbable. The relation between the agent and the tree that is such that the tree is climbable is a relation between the body (B) of the agent and a part of its environment (E). This relation holds in virtue of a certain range of the causal properties of its body (B1, B2, B3, … Bn) and those of the environment (E1, E2, E3, … En). Now consider an instance where an agent experiences her arm as able to be moved into a particular position. Where such an experience is veridical, here we have an instance of the same general relation, but instead the relation in question holds between an agent’s body as a whole and the parts of its body. More fully, here there is a structural affordance relation between an agent's whole body (W) and its parts (P). And this relation holds in virtue of a certain range of the causal properties of its body as a whole (W1, W2, W3, … Wn) and its parts (P1, P2, P3, … Pn). A final aspect of the definition of structural affordances is that they are first-order affordances relations that themselves enable agent-environmental affordance relations. Agent-environmental affordances constrain and enable the possibilities of an agent's bodily interaction with its environment. But such possibilities obtain only in virtue of the possibilities provided by structural affordance relations.

The assumption that certain phenomena of bodily experience must be explained in terms of structural affordance relations is one that requires independent defence. My aim is not to defend that assumption here but to show that it allows us to conceive of a robust sense in which bodily experience may be strongly embodied. Structural affordances are relations inherent to the actual structure of the body that constrain and enable the possibilities of an agent's bodily movement. To the extent that an agent's experience of its body is constituted by the actual

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possibilities of its bodily movement, structural affordances have an explanatory role to play.

There are various ways in which the putative existence of mental representations of parts of the body might be consistent with and even complement such a strongly embodied account of bodily experience. I will describe one such possibility that admits the existence of mental representations of parts of the body but denies the existence of mental representations of the body as whole.

We need first to fix the term ‘mental representation’ such the explanatory role of mental representations of the body is independently plausible. By stipulation then, mental representations of the body are dynamic models, certain of which have the function of adaptively tracking the spatiotemporal dynamics of that which they represent. On the strongly embodied view suggested here, parts of the body may be represented and relations between parts; what is not represented is the body as a whole.

On a common conception of the reference of a term such as the 'body image', it is thought to pick out a mental representation of the body as a whole and only derivatively a representation of its parts. Such a representation might keep track of the spatiotemporal dynamics of the whole body and its parts. It might thereby contribute to an agent's experience of parts of its body as situated within the whole.

The account suggested here denies the necessity of positing such a representation. The alternative proposal is that a cognitive system might minimise internal representation by exploiting the causal relations that obtain within the actual body, the causal relations that enable structural affordances. In this way, adaptive representation of the spatiotemporal dynamics of parts of an interlocked structure can occur without representing that structure as a whole. On this strongly embodied view, bodily experience depends on more restricted body representations, none of which keep track of the body as a whole. The fact that parts of the body seem situated in the body’s interlocked structure, is simply due to the structural affordance relations that obtain within that structure.

Predictive Perception of Sensorimotor Contingencies: Explaining perceptual presence and its absence in synaesthesia

Anil Seth[1]

Abstract. Does perception involve the deployment of predictive models conducting inference on the causes of sensory signals, along Bayesian-brain lines? Or does it depend on the skilful mastery of sensorimotor contingencies, as sensorimotor theories suggest? Here I describe a reconciliation of these distinct perspectives by the theory of Predictive Perception of Sensorimotor Contingencies (PPSMC). In PPSMC, generative models underlying perception incorporate explicitly counterfactual elements related to how sensory inputs would change on the basis of a broad repertoire of possible actions, even if these actions are not executed. These counterfactually-extended generative models encode SMCs related to repertoires of sensorimotor dependencies. PPSMC extends predictive processing approaches to account for the phenomenology of ‘presence’ which, following sensorimotor theories, refers to the subjective reality of perceptual contents. PPSMC is also able, unlike sensorimotor theories, to account for the absence of perceptual presence in atypical cases like synaesthesia.

Normal perception involves experiencing objects within perceptual scenes as real, as existing in the world. This property of “perceptual presence” has motivated “sensorimotor theories” which understand perception to involve the mastery of sensorimotor contingencies (SMCs) [1]. These ideas inherit from Gibsonian notions of “affordance” and from enactive cognitive science, both of which stress the importance of brain-body-world interactions in cognition, perception, and action [2]. On sensorimotor theory, the perception of (for example) a tomato as perceptually present is given by practical mastery of the SMCs governing how sensory responses elicited by the tomato will behave given specific actions (like eye movements). A strong point of this theory is that it suggests why there are differences in qualitative character between modalities, the reason being that different modalities instantiate different SMCs. However, sensorimotor theory faces two major challenges. The first is to specify at the level of neural mechanism what is meant by a SMC and by their mastery. The second is to account for instances of perception which apparently do not involve SMCs.

Synaesthesia is a good example of the latter case. Grapheme-colour synaesthetes, for example, have “concurrent” experiences of colour when viewing achromatic graphemic “inducer” stimuli [3]. Yet these inducer stimuli, by definition, do not engage SMCs associated with red objects. This poses a problem for sensorimotor theory. In addition, synaesthetic experiences typically lack perceptual presence: synaesthetes usually know that their concurrents are not actually part of the real world. Current theories of synaesthesia – like those suggesting “cross-activation” between brain regions involved in inducer and concurrent processing - do not account for this critical phenomenological property.

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An alternative theoretical tradition sees the problem of perception as essentially one of inference about the causes of sensory signals. These “Bayesian brain” or “predictive processing” theories, which can be traced back to von Helmholtz in the 19th Century, are gaining increasing influence within cognitive neuroscience [4-6]. Here, the basic idea is that, in order to support adaptive responses, the brain must discover information about the likely external causes of sensory signals, without any direct access to these causes, using only information in the flux of the sensory signals themselves. Perception solves this problem via probabilistic, knowledge-driven inference on the causes of sensory signals. Applied to cortical networks, the concept of predictive processing overturns classical notions of perception as a largely “bottom-up” process of evidence accumulation or feature detection. Instead, predictive processing proposes that perceptual content is specified by top-down predictive signals emerging from multi-level hierarchically-organized generative models of the causes of sensory signals, which are continually modified by bottom-up prediction error signals communicating mismatches between predicted and actual signals across hierarchical levels. In this view, even low-level fine-grained perceptual content depends on a cascade of predictions flowing from very general abstract expectations which constrain successively more detailed predictions.

While accumulating evidence is providing strong (though indirect) support for predictive processing theories, these theories have not so far addressed the key challenge of perceptual presence as identified within sensorimotor approaches. Neither have predictive processing accounts of synaesthesia yet been developed. Finally, sensorimotor and predictive processing theories have developed largely independently, with opportunities for their integration not fully appreciated.

Here, I describe a new theoretical approach, Predictive Perception account of SensoriMotor Contingencies (PPSMC), which addresses these three challenges [7]. The core idea of PPSMC is that generative models underlying perception incorporate explicitly counterfactual elements related to how sensory inputs would change on the basis of a broad repertoire of possible actions, even if these actions are not executed. These counterfactually-extended generative models encode SMCs related to repertoires of sensorimotor dependencies. Critically, perceptual presence in PPSMC depends on the degree of counterfactual richness: A counterfactually-rich generative model will endow perceptual content with presence, while a counterfactually-poor model will result in perceptual content lacking in presence.

PPSMC offers a number of innovations as compared to sensorimotor or predictive processing approaches considered separately. First, the concept of a counterfactually-rich generative model provides a neurofunctional operationalization of the “mastery of sensorimotor contingencies” central to sensorimotor theory. Second, it extends predictive processing to account for the fundamental phenomenological dimension of perceptual presence. Third, it suggests a solution to the challenge presented by synaesthesia: While the generative models underlying normal perception are typically counterfactually rich (reflecting a large repertoire of possible sensorimotor dependencies), those underlying synaesthetic concurrents are hypothesized to be counterfactually poor. Fourth, the theory naturally accommodates phenomenological differences between a range of experiential states including dreaming, hallucination, and the like. And finally it may enable a new view of the phenomenological (in)determinacy of normal perception.

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Perceptual presence enacted. Commentary on Seth's predictive processing theory of sensorimotor contingencies

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Abstract. We challenge the necessity of the representationalist assumptions underlying Seth's predictive processing account of sensorimotor contingencies. We point at an alternative embodied/enactive conception of perception, and at the possibility of nonrepresentational sensorimotor accounts of both sensory presence and synaesthesia.

Is cognition, in a broad sense which includes perception, always and everywhere underwritten by representations? Cognitivist theory, including the increasingly influential "predictive processing" branch as exemplified in Seth's target paper [1], answers that question in the affirmative. Hohwy expresses this felt necessity for representation by stating: "The brain needs to represent the world so we can act meaningfully on it", quickly connecting with the "Bayesian brain" idea by adding: "that is, it has to figure out what in the world causes its sensory input. Representation is thereby a matter of causal inference" [2].

Many embodied/enactive theorists (E-theorists, for short) defend the opposed idea that much intelligent action is possible without representation (e.g. [3, 4, 5]). They hold that one can perceive the world, and act meaningfully in it, without representing it. They will agree with Bayesian modellers like Hohwy and Seth that intelligent action requires that an organism is systematically sensitive to the statistical structure of their environment. But they will hold that the presence of such sensitivity does not imply that the organism has to contain some inner description or model of those probabilistic patterns. Organisms respond to or enact that relevant structure in their adaptive actions, without relying, and without needing to rely, on representations that prescribe what to do, much like the solar system "acts out" Newton's laws of planetary motion without in any way representing them. E-theorists think that, for a large share of intelligent activity (including perception), it is just as unnecessary to resort to explanations in terms of representations, as it is unnecessary to see planetary motion as driven by inner astronomical models.

A prominent cognitivist motivation for the need for representation is the observation that some cognitive phenomena, also of perceptual stripe, can occur outside of their normal contexts – as in hallucinations, or in synaesthesia. If it is beyond doubt that one is not experiencing an environment in these cases, mustn't one then be experiencing a representation of the environment then? In response, the E-theorist can point out that quasi-perceptual phenomena like hallucination or synaesthesia should be construed as re-enactments of perceptual experiences, be it in the absence of the external patterns normally causing them. From the perspective of the E-theorist, the enactment of perceptual experience is nonrepresentational, and the re-enactment of perceptual experience is so too. Presence or absence of characteristic patterns in the environment doesn't change the status — representational or not — of the experience.

A fully nonrepresentational version of the sensorimotor contingency theory will explain the feeling of perceptual presence by an organisms' interaction with a situation which shows bodiliness and grabbiness: a situation in which an organism's movements, as well as changes in the environment, will have systematic changes in the way it is perceptually affected by the environment (e.g. [6]). An organism experiences a tree as a real, solid and three-dimensional object, because it is attuned, in its further interaction with the three, to the properties the tree genuinely has – which the organism can encounter in its further interactions with the tree. In addition, there are properties particular to the mode of interaction itself, such as that in vision, closing the eyes makes the sensory stimulation temporarily come to an end. Attunement to properties, so the E-theorist insists, is possible without representation of those properties. Attunement can be misaligned, and an organism can act and experience in a way attuned to a tree— when what's in front of it is not a tree. In a richly interactive situation, further interaction will counteract misaligned attunement. An organism will quickly find its misalignment caused by a reflection of a fly in the pond when it moves to catch it. But if nothing counteracts a misalignment, it might linger on, perhaps even become systematic. Of course, not being counteracted isn't the same as being supported by the environment – as a genuine experience of a fly could or would be. Merely non-counteracted experiences are objectively different from supported experiences, and that difference can show up in experience as a difference in felt presence.

It seems therefore, that, contrary to the assumption that the sensorimotor account "struggles to explain instances of perception, such as synaesthesia" (as in the abstract of the target paper), it does have means to account for the difference in felt presence between perceptual and synaesthetic experience. Synaesthetic experiences might be merely not-counteracted experiences, different from genuinely perceptual experiences in that only the latter are congruent with patterns in the environment. Such congruence need not be understood in the match of an inner model with a structure in the world. It can consist in nothing more than the enactment of a pattern of interaction which unfolds in the way it has unfolded in the organism's past.

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Searching for the roots of experience: Early nervous systems and the origins of the animal sensorimotor organization

Fred Keijzer[1]

Abstract. How did the earliest nervous systems evolve and how did the animal sensorimotor organization first take shape? The Skin Brain Thesis holds that nervous systems first arose not to connect sensors to effectors, but to generate a new kind of effector – *muscle* – and primarily functioned as a way to integrate whole body movement. Bodily sensitivity to self-induced motility subsequently provided a new sensing device that operated at a whole bodily scale. Such a skin brain organization can be contrasted to an input-output interpretation of both basic nervous systems and the animal sensorimotor organization. Close conceptual links can be drawn between early nervous systems and the animal sensorimotor organization, making it thinkable in a concrete way that nervous systems and the animal sensorimotor organization are not standard input-output devices on a par with current computers and robots. New options for redrawing the roots of the sensorimotor organization behind experience result.

How did the earliest nervous systems evolve and how did the animal sensorimotor organization (ASMO) first take shape? These two questions are intimately related. Nervous systems are closely tied to and even a necessary condition for the sensorimotor organization that is characteristic for animals. At the same time, animal abilities to move and sense are a necessary requirement for nervous systems to function. Both must have co-evolved from simple beginnings to the many different forms that currently exist. How did this co-evolution first occur?

While interesting in its own right, this question may seem far away from human experience and the human brain. Nevertheless, for sensorimotor accounts of experience this question is highly relevant as it targets the connection between neural systems and sensorimotor organization in its most basic biological form. While this remains far away from the human condition, it will help to clarify two basic questions: "What are nervous systems?" and "What is an animal sensorimotor system?" Having better answers to both questions will allow a better understanding of their relation and subsequently of the kind of organization on which human experience depends.

Early nervous systems stress a *biological* context for looking at basic nervous systems. This is an important switch as many cognitive and neuroscientists regularly use artificial cases as basic examples (e.g Braitenberg vehicles or robots). However, we should not simply assume a deep similarity between artificial control structures and nervous systems, nor between sensorimotor artifacts and the ASMO. Early nervous system evolution is a good biological test case where these standard preconceptions can be questioned.

These preconceptions can be described as a commitment to an input-output view for both nervous systems and for the ASMO: Nervous systems – usually cast as 'the brain' – are complex systems, only connected to the world through sensors and effectors – providing both input and output – while the relevant ASMO is constituted by these sensors and effectors. In addition, nervous systems are often interpreted as information processing devices, like computers, while the ASMO is cast as the animal version of a robotic device. While this general description may strike many as obviously correct in a rough and general sense, this description can actually be challenged when one turns to the early evolution of nervous systems.

This challenge comes in the form of the Skin Brain Thesis (SBT) (Keijzer, Van Duijn & Lyon, 2013). Following early work by Chris Pantin, the SBT holds that nervous systems first arose not to connect sensors to effectors, but to generate a new kind of effector: *muscle*. Muscle provided a much more powerful and large-scale source of motility than earlier cell-level means of locomotion, such as cilia. However, such contractions must be coordinated across the whole animal body in order to be effective and require dedicated forms of fast signaling: nervous systems. According to the SBT, early nervous systems did not merely connect sensors to effectors, they helped build up a new kind of effector. Early nervous systems enabled a switch to

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motility by coordinated multicellular body-contractions, which is a key evolutionary event for the animal sensorimotor organization.

According to this skin brain account, early nervous systems – diffusely connected nerve nets – evolved from contractile epithelia – 'skin' – in a step-wise process, first evolving synaptic transmissions to neighboring cells and later axodendritic processes that enabled transmission across longer distances. In both cases, the prime directive was to generate and control self-organized patterns of globally coherent activity across an organism's contractile surface, integrating the dynamical motile aspects of the organism into a single unit that is sensitive to its own body-movements. For easy reference this process will be called *Pantin patterning*.

While the SBT initially targets the effector side of the ASMO, it has also repercussions for sensing, interpreted as detecting and using environmental features. First, a skin brain organization provides an important precondition for multicellular sensory arrays. Second and more fundamental, a skin brain organization turns the multicellular body itself into a sensing device that does not necessarily requires external sensors (Keijzer, 2014). Pantin patterning involves sensitivity to the configuration of the ongoing dynamical extension-contraction patterns within the animal body. Such sensitivity makes the dynamical movements of the body a variable that can be controlled by the organism. As bodily movements are themselves constrained by environmental features that either hinder or allow motility, bodily sensitivity alone allows the rudimentary sensing of the environment at this bodily scale. The result provides the outlines of a basic form of sensorimotor organization that is organized at and sensitive to environmental features at the level of a multicellular animal body.

The important issue here is that the SBT sketches how a basic multicellular organization can evolve that is tailored for sensorimotor interactions with bodily-scaled surface arrays in the environment. Instead of taking a high-level description of a sensing and acting organism in an environment as a precondition, a skin brain scenario specifies how such a complex sensorimotor organization can have come into being from a more basic set up. In this scenario, sensors and effectors are not basic, but derive from a fundamental skin brain organization.

While the SBT is tentative and limited to basic forms of nervous systems and the ASMO, the conceptual implications are important and immediate. First, the SBT provides an evolutionary account that draws necessary conceptual links between sensing and motility. Second, nervous systems themselves become conceptually linked to the ASMO. Third, the SBT makes it thinkable in a concrete way that nervous systems and the ASMO are not standard input-output devices on a par with current computers and robots.

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Attunement, habits, and knowing what to do

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Abstract. 'Recognizing' and 'registering' are cognitive/representational metaphors for the brain's tuning to sensorimotor interdependencies which should be avoided by a sensorimotor account of consciousness ('SMAC'). Other accounts of the vehiculars as well as of 'cognition' at the level of sensorimotor interdependencies are wanted. In some prominent versions, however, SMAC also clearly acknowledges a truly cognitive level, for which the cognitive metaphors (exclusively) should be reserved. In our presentation we take advantage of John Dewey's considerations on habits: A habit is a tendency which controls future experiences conceived as an executive skill by uniting stimuli and actions in order for the organism to achieve its goal. Dewey's account points in the direction of a presentational kind of 'knowing what to possibly do', to be distinguished from orthodox accounts of 'knowing how' and 'knowing that'. Different forms of this 'type' of knowledge as well as various empirical support and objections are discussed.

As it has been pointed out (e.g. by Block, in [1]), 'recognizing' and 'registering' are cognitive metaphors for the brain's tuning to sensorimotor interdependencies which should be avoided by a sensorimotor account of consciousness ('SMAC'). These metaphors give associations to the familiar ballpark where representational theories (like e.g. HOP, HOT, HOST) reigns - theories which SMAC goes against. Hence other accounts of the vehiculars at the level of sensorimotor interdependencies are wanted. On the other hand, SMAC in some versions (e.g. [2, 3]) clearly acknowledges a truly cognitive level, for which the cognitive metaphors (exclusively) should be reserved.

Firstly our presentation deals with the question of what alternative model might fulfill the role of the vehiculars at base level. Secondly we discuss how to get the higher-order cognitive level right in order to explain a subject's conscious presentation of the world due to its implicit knowledge of sensori-motor contingencies without invoking neither representations of these, nor representational properties 'trickling down' into the base-level.

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With respect to ‘the vehicular problem’, we suggest that John Dewey’s considerations on habits are useful towards uncovering the SMAC-compatible processual underpinnings, and thus be more than just another non-representational metaphor of the ongoings at this base level. Dewey’s account of habits makes a presentational kind of ‘knowing what to possibly do’ understandable, a form of knowledge which is different from the orthodox accounts of ‘knowing how’ and ‘knowing that’ respectively. Different conceptions of ‘knowing what to do’ are tried out in our presentation, and some empirical supportive cases [4, 5] and objections [6, 7] from blindsight, sleepwalking and related visuo-motor phenomena are discussed.

Human actions exhibit stable relationships to worldly affairs in terms of organizational patterns of relations between actions and perceptions. These patterns can be understood through Dewey’s conception of habit: The nature of a habit is a tendency that controls future experiences conceived as an executive skill by uniting stimuli and actions in order for the organism to achieve its goal [8, 9, 10]. It is the unifying structure which actively looks for stimuli to appear and selects the impulses given the registered stimuli. On the other hand, the stimuli searched for by habit are selected on the background of the change of the surroundings which they make possible. Habits play constitutive (qua functional) roles for conscious experiences, not only for unconscious actions. As Dewey notes: without “entering into organization with things which independently accomplish definite results, the eye stare blankly and hand moves fumblingly. These organizations are habits.” [9].

Thus a habit is not to be understood in ‘the’ folk psychological sense of the word: Surely we often take habits to be patterns of behavior that we have repeated enough times to be able to perform them unconsciously. But according to Dewey, this conception gets it the wrong way around: “[…] [I]t is truer to say that we repeat because we have habits, than that we form habits because we repeat” (Dewey, op.cit.).

Hence Dewey is not only the first (proto)SMAC proponent, but his conception of habits helps answering the question why we see what we see: What is perceivable are the (gibsonian) ‘invariants’ affording an organism to act, made possible by habits.

With respect to our second issue, perceptions are constituted by implicit knowledge of sensorimotor contingencies, which is neither to be understood as ‘knowing how’ nor ‘knowing that’ but rather as a complex and dynamic kind of ‘knowing what to possibly do’. Thus, perception is always relative to knowing ‘what I am doing’ or ‘what I am inhibited in doing’ and characterizable as “knowing what possible to do in relation to a specific stimulus”: a knowledge constituted by (deweyan) habits. Therefore, no knowledge of ‘sensorimotor contingencies’ exists in the standard sense of propositional knowledge: the ‘sensorimotor contingencies’, form part of ‘knowing what to possibly do’.

This conception of knowledge is not without problems. Above presenting different forms of this ‘type’ of knowledge as well as various empirical support and objections, we also discuss the objection that ‘implicit knowledge of what to possibly do’ really isn’t knowledge at all, but ‘merely’ a kind of belief.

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