Collaborative Project

eSMCs

Extending Sensorimotor Contingencies to Cognition

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1 Introduction

Cognitive Science has witnessed as set of transformations since its original foundations in the 1950's and 1960's. One such transformation involves the central role that the body is considered to play in cognitive processes, which are now seen as far from the abstract (disembodied) symbolic computation that cognition was originally taken to be. The experience of the lived and living body, its direct interaction with the environment, its synergetic articulation of action and perception are progressively being incorporated into the theoretical foundations of the field and many of its practical applications. During the last decade sensorimotor contingency theory (SMCT) (O'Regan and Noë, 2001) has attracted increasing attention as a fresh departure point for re-thinking perceptual awareness in terms of action (with the potential to extend the new foundations into other domains of cognition), rather than as originating in the passive impression of an external world upon sensory organs. What is put at the center of cognitive theory is the way in which sensation changes as a function of motor variations or to be more precise, how sensory and motor activity *co-vary*. When considered in this way a form of action, perception is not directly about the state of affairs in the world, but rather about the regularities that govern the way in which movement and sensory variations change together.

Despite the early controversy and the wide recognition of the potential of this approach, and partly due to a prevalent focus on its philosophical implications for a theory of perceptual consciousness, there have been few attempts to operationalize the concept of sensorimotor contingency (SMC) and to fill in the gaps that separate a SMCT of perception from a SMCT of cognition. We here summarize a large body of work generated, in large part, within the eSMCs project, and aimed at overcoming this gap by: a) describing the theoretical landscape of SMCT and its relationship with other embodied theories of cognition (section 2, summarising results presented in deliverable D1.1), b) providing operational definitions of the notion of SMC and related concepts, both within dynamical and probabilistic frameworks (section 3), c) giving a critical examination of whether possession of sensorimotor knowledge implies internal modelling or simulation (section 4, drawing on D1.1 and further developments), d) facing the empirical and conceptual challenges to an essential or constitutive role of SMCs for perception and cognition, and, finally e) extending the framework to address some of the necessary steps towards a full fledged SMCT of cognition: namely agency, habits, skills, plasticity and temporality.

2 The place of sensorimotor approaches within embodied cognition

As part of the task of expanding the theoretical basis of the sensorimotor contingencies theory, it is important first to situate this approach within the wider set of embodied approaches to the mind. This objective was achieved in preliminary fashion in Deliverable D1.1 (*Interim report on eSMCs and embodiment*), but in this section we give a condensed and improved summary of those findings, before going on to present novel work in subsequent sections. This fulfills the double purpose of presenting the reader with a more definitive and concise message about the relation between SMCT and other approaches to embodiment and of preparing the ground for the ensuing discussion on the operational and probabilistic analyses of sensorimotor contingencies which have been developed within the project.

2.1 Embodiment in cognitive science

Embodied approaches to cognition come in all kinds and flavours and with enough differences between them to question the existence of a common programme, method or theoretical commitment. However, if we were to ask self-proclaimed embodied cognitive scientists (or neuroscientists, or psychologists) about what is the core message of their embodied approach to the mind they would probably agree with the statement: *The body is crucial for the mind*. But divergences would immediately be noticeable as we query this statement further. Crucial in what sense? For explaining the mind? For realizing the mind? For developing a mind? What specific aspects of the body make it crucial? And what exactly should we understand as 'the body'? Is the body merely causally crucial or is there something about the essence of the mind that requires embodiment?

Different approaches respond to these questions differently, nevertheless there is something in common in the various ways of interpreting this statement. What seems to be the common ground is a rejection of a traditional cognitivist framework that dominated cognitive science for decades and saw the mind exclusively in terms of computations performed in the brain. This rejection can be moderate (arguing that not every aspect of cognition is a computation in the brain) or radical (saying that there are no computations in the brain, that the brain does something else), but all embodied approaches explicitly leave behind at least some assumptions and methods of the traditional cognitivist framework.

In this section we briefly describe the philosophical framework to which cognitivism belongs: functionalism. This is followed by a reminder of the role of the body in cognitive linguistics and autonomous robotics, as the initial sub-disciplines within cognitive science where embodied ideas started to make a strong impact in the 1980s and 1990s. Then we look at examples of embodied approaches which attempt to bring the body back into the functionalist framework (extended functionalism) or which reject the latter (enactivism). We find that SMCT, with specific claims of its own, is placed somewhere between these positions. One of the reasons for this is that its theoretical statements remain open to different kinds of interpretation thanks to the fact that the core terminology of the approach lacks clear and accepted operational definitions (to which we turn in Section 3).

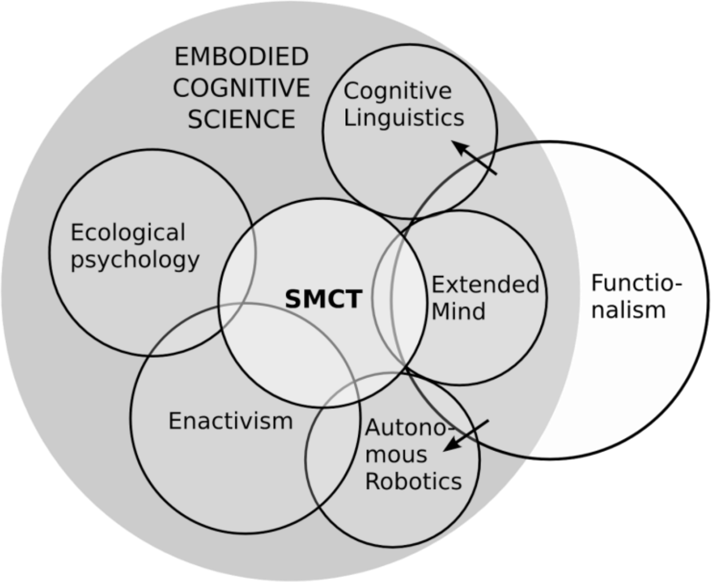

Figure 1: A map of different schools within embodied approaches to cognitive science. See text for detailed explanation.

2.1.1 Functionalism

Cognitive science inherits strong theoretical commitments from cognitivism and Artificial Intelligence (AI). Since the beginnings of the AI in the 1950s, the measure of the mind, and the target of the discipline, was human abstract reasoning. This was conceived as disembodied, formal, and symbolic. In other words, intelligence was best described as computational, which helped introduce a fruitful separation between computed functions and implementation details (e.g. Marr, 1982). Cognitivism thus marked a break with behaviourism, and its claim that the inner workings of the mind were simply scientifically inaccessible. However, the divorce between the domain of the mental and that of the underlying physical medium rests on the assumption that mental states can be identified with their *functional* role only, i.e., their causal relation to other mental states and their eventual role in the production of behaviour.

Traditional functionalism of this kind thus concerns itself with the distinction between syntax and semantics. Mental states, e.g., beliefs and desires, explain behaviour in terms of meaning (semantics). The claim of traditional functionalism is that the right physical states could be set up, so that they interact with each other and lead to eventual behaviour in the way required for the semantic description to hold true. It is then argued that such physical states simply *are* the beliefs, perceptions, and desires of agents (more precisely, beliefs and desires are whatever fills that functional role, which in this case is the given physical states). Furthermore, an evolutionary approach to semantics (e.g., Millikan, 1984) complements this view, seeking to ground the origin of such physical, but normative, states in Darwinian evolution. Very roughly, ‘good/right’ equates to ‘would have led to survival in the evolutionary past’ and ‘bad/wrong’ equates to ‘would have led to death’.

Computationalism (aka cognitivism) claims that these physical states are updated according semantics-respecting rules, with the brain as the computer hardware. The whole agent, then, is seen as a physical symbol system, with input and output interfaces, a memory, a processor and some form of internal clock. The standard cognitivist claim, inspired by the Church-Turing thesis, is that *any* functional description can be implemented in a fast enough general-purpose computer, and that any physical agent can be understood as being such a computer.

Unsurprisingly, in traditional functionalism the body plays a secondary role; it is something controlled in the right way by a brain. Brains themselves are what have beliefs, desires, thoughts, feelings and perceptual sensations (they just need to be linked up in the right way to sensors) and can act (they just need to be linked up in the right way to actuators).

2.1.2 Non-trivial roles for the body

Although criticisms of traditional functionalism have existed since the 1970s (e.g., Dreyfus, 1972), it was in the 1980s that cognitive linguistics and autonomous robotics began to question brain-centered computationalism and to offer positive alternative explanations of aspects of cognition in terms of bodily structures and the interaction with the environment.

In cognitive linguistics, the work by George Lakoff and Mark Johnson had a strong impact on cognitivism (Lakoff and Johnson, 1980). One of their main contributions was on the problems of *meaning* and *concept formation*. Human language reveals a deep entanglement between spatio-temporal experience and the meaning of even the most abstract concepts. The body, far from being an implementation detail, is a source of meaning, concept articulation and even reasoning. Lakoff and Johnson argue that metaphors, not logical deductions, are the primary tools for thinking and it is through re-framing problems and situations in an embodied context that we reason most of the time. The relative size, orientation, shape and articulation of the human body anchors our understanding of the world and the meaning of our linguistic utterances. For instance, metaphors of progress or future orientation are often linked to the idea of 'advance' ('the plan is moving forward', 'we're ready to go', 'there's a stumbling block', etc.) and this is rooted in our bodily schema for walking in the forward direction. Other abstract ideas like 'sets' or 'containment' are similarly rooted in our bodily notions of inside/outside. We see here a first clear meaning to the statement: the body is crucial for the mind.

These critical insights coincided in time with a frustration in generating artificially intelligent systems capable of acting in the real world using the ideas of cognitivism and the proposal of alternatives based on embodied design principles (Brooks 1991; Beer 1990; Harvey et al. 1996; Pfeifer & Scheier 2001). Cognitivism led to a linear "sense-model-plan-act" architecture in robotics: sense and encode environmental features to update an internal model of the state of the world, plan and reason using such an internal model to deduce the appropriate strategy and initiate a motor response. Instead of a top-down strategy (abstract thought to concrete action), roboticists successfully applied a bottom-up approach: starting from simple behavioural layers (e.g., collision avoidance) and scaling up to more complex behaviour (emerging from the interplay between robust sensorimotor layers and their direct interaction with the environment).

In the larger picture, if embodiment and situatedness are indeed crucial for the design of successful autonomous robots, a lesson could be drawn for the study of cognition in general: the assumption of a top-down, central processor at the core of cognition is questionable and biologically implausible. Indeed, as we study the evolution of intelligent behaviour, we find that cognitive capacities build upon opportunistic adaptations that take advantage of robust synergies between bodily structures, behaviours and the environment.

Both in situated robotics and in cognitive linguistics we can recognize the germ of SCMT ideas: the role of the body schema and habits in shaping thinking in cognitive linguistics, and the centrality of dynamical sensorimotor embeddedness in situated robotics.

2.1.3 Different conceptions of the body: Extended Mind and Enactivism

The lesson from cognitive linguistics and situated robotics was clear: the body is crucial for cognition. The question was how to interpret this lesson more generally. One way is not to throw away the central computational commitments of functionalism, but merely to abandon those aspects it seemed to have got wrong, namely: that computations occur exclusively in the brain; that they must be of symbolic in kind; and that they must describe exclusively propositional thinking.

In this vein, functionalism has developed an ‘extended’ variant (Clark & Chalmers 1998; Wheeler 2011). This ‘extended mind theory’ includes the possibility that the physical vehicles of functional states can extend out of the brain into the body and perhaps into aspects of the external world (for instance, tools). The paradigmatic example, provided by Clark and Chalmers (1998), is that of a notebook becoming, in certain cases, an essential physical part of the mental state of memory. Another way of interpreting this claim is to say that we can sometimes ‘offload’ some of the ‘computation’ into the body and world, freeing the brain from having to compute everything. There is a functional equivalence between cognitive processes inside and outside the skull.

The body plays a dual role in extended functionalism. It is both part of mental states and processes, but also controlled by them. It has no special status. It is simply a part of the apparatus that sometimes achieves relevant computations. Its role is only functional. It is seen as a brain-external process that is part of the cognitive system only to the extent that we would call its contribution cognitive were it to go on in the head (parity principle). Essentially, extended functionalism takes embodiment as just a form of signal pre-processing external to the sense organs, a form of offloading control and computations into body synergies, tools and objects.

The body is conceived in a radically different manner by full-blown enactivism[1]. As employed by Varela, et al., (1991) and recent articulations (Di Paolo, et al., 2010, Thompson, 2007), this term describes an attempt to naturalize the mind, not as a functional economy of representational states, but based on the organization of living systems. Instead of the body merely being a container or an instrument controlled by the brain, in an enactive perspective the body is directly linked to the concept of *autonomy* and thus acquires a non-negotiable role. Bodily identity is closely tied to the autonomous processes of self-construction that become interlinked in it. These include metabolic and other physiological processes (nervous system, immune system, etc.) as well as the closed, self-sustaining loops of interaction with the world (habits).

According to enactivism, this notion of the body already counts as a cognitive system because it is possible to deduce from metabolic and other forms of self-production, the notion of *sense-making*, i.e., a perspective of meaning on the world invested with interest for the agent itself, a subjective viewpoint from which interactions with the world are evaluated (Di Paolo 2005, Barandiaran & Moreno 2006). For enactivists, this intrinsic normativity provides a non-circular *definition* of cognition. There cannot be a mind without a living body.

2.1.4 Ecological psychology

Ecological psychology championed the idea of perception as an agent's active exploration of the environment through invariants in its sensory array as it undergoes transformations caused externally or by its own movement (Gibson, 1979). Such agents visually perceive permanent properties of the environment, it is suggested, by directly picking up invariants from the optic array. Of particular interest are affordances – i.e. those invariants that specify possibilities for actions an agent can perform in its environment. Such affordances are thought to exist objectively in the world, independent of whether or not an agent is in fact (capable of) perceiving them, but at the same time are dependent on an agent's bodily abilities (e.g. a set of stairs might be perceived by an adult as serving to reach a different floor in the building, but for a small child it might constitutes an unscalable obstacle).

The role of the body in ecological psychology is ambiguous. On the one hand, sensory invariants can be discovered by transformations (e.g. change in perspective) that may or may not be produced by the agent's self-motion. While a particular motor pattern might be required in some cases to discover an invariant, its role is merely instrumental. On the other hand, the agent's particular embodiment is an essential part in the constitution of affordances, the fundamental building blocks of ecological psychology. In other words, the body is an important constraint on the kinds of affordances that can exist in the world, but in the process of perceiving (and acting on) them it plays an instrumental role only. Agents (and their embodiments) are considered not so much as constructing environments, but as exploring them. This is in keeping with the

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[1] In order to avoid confusion, we note that in literature specifically concerned with SMCT, the term enactive is often used to denote the SMC research programme itself. In this document, we reserve the terms 'enactive' and 'enactivism' for the more radical form of enactivism described here.

concept of motor equivalence across different body plans, i.e. the idea that different organisms can perceive the very same affordances (e.g. time-to-goal; Lee, 1976).

Normativity plays a role in ecological psychology only insofar as affordances are defined as possibilities for action, implying that agents perceive invariants that mediate adaptive, goal-directed behaviour. Unlike enactivism, however, it makes no attempt at grounding this goal-directedness in the self-constitution and autonomy of the agent. In this and other ways, the Gibsonian approach has much in common with the SMC approach, and is explicitly (c.f. Noë, 2004) acknowledged as a direct precursor of it.

2.1.5 Sensorimotor contingency theory

O'Regan and Noë (2001) have presented a view of perception in which the body also plays a central role. Depending on the interpretation, their proposal can be seen as closer to extended functionalism or to enactivism. As we act in the world, certain sensorimotor regularities or contingencies (SMCs) occur: sounds get louder as you move towards their source; different parts of objects come into view, as we move around them. More generally, the way in which our sensory input changes tends to vary in *lawful* ways as our bodies move in the world.

Building on this insight, O'Regan and Noë go on to argue that the perceptual experience of vision is constituted by the mastery of those SMCs, which affect a creature with eyes moving around the world. Similarly, mastery of touch is the mastery of the changing tactile and proprioceptive sensations that occur as one moves one's skin in contact with objects in the world; and so on. As they would put it, one cannot perceive unless one has mastery of these changes in sensory stimulation as a result of movement (in Section 4, we come back to whether this claim should be interpreted in causal or constitutive terms). Thus, for SMCT, the active body is crucial for perception both in a developmental sense (how we learn to master SMCs) and as skills are exercised in action.

In both ecological psychology and SMCT, perception is considered action-dependent. How then do ecological invariants differ from sensorimotor contingencies? One way to distinguish the two has been proposed by Mossio and Taraborelli (2008). In the ecological approach, invariants are considered properties of the sensory array that are discovered by transformations, but the particular motor patterns that bring about these transformations are considered irrelevant. In the sensorimotor approach, on the other hand, the invariance is to be found exactly in the *relation* between motor commands and sensory signals. As such, specific self-generated movements can be considered *constitutive* of sensorimotor invariants, whereas they are merely *instrumental* for ecological invariants. Or as the authors also put it, while in both cases action-dependent in a loose sense, "perceptual information is characterized as motor-specific in the case of sensorimotor invariants and transformation-specific (and motor equivalent with respect to movement) in the case of ecological invariants (Mossio and Taraborelli, 2008).

Arguably the view implied in SMCT has the potential advantage of putting the whole agent, rather than just the brain, at the center of the story. Perception and other cognitive states are not in the brain, not even in the head, but emerge from the interaction process itself. Even the simplest movements (moving an eye, adjusting the position of the head) are things, which a whole agent does, and which are norm-governed at the agent-environment scale. In this sense, SMCT leans towards the insights of even the most radical forms of enactivism.

The SMC view does not, however, answer the question of how norms arise, or of what distinguishes mere movements from acts. It has no defined notion of self or agency; nor does it explain explicitly (if at all) aspects of perceptual experience, which are not apparently provided by the mastery of SMCs, such as their first-person givenness or the integration of different forms of SMCs into multi-modal perceptual wholes. Similarly, SMCT presupposes the presence of a body (and a subject, see Thompson 2005), because it takes the body's structure and possibilities for action as its starting point. In these aspects, and in the various ways in which terms such as "mastery or knowledge of the laws of SMCs" can also be interpreted in more traditional functional terms, SMCT may seem more like another version of extended functionalism.

2.2 Representations in embodied cognitive science

A particularly contentious issue when querying the role of the body in cognition is the role of internal representations — the theoretical and empirical currency of cognitivism. Here we sketch briefly where and how the attitude of SMCT toward representations fits into the context of related programs.

2.2.1 The role of representations within less cognitivist approaches

For *extended functionalism,* even though the concept has been transformed in various ways (e.g., action–oriented representations, Wheeler 2005), and even if it is noted that some cognitive performances might not require them, representations remain an essential part of the theory. What distinguishes cognition is precisely the manipulation of representations, whether they are contained in the skull or extended into the world. In *embodied cognitive linguistics* representations remain equally essential to cognition, but they here lose their propositional and referential nature, becoming instead figurative and subsidiary upon bodily experience. On the other hand, in *situated robotics*, the notion of representation is all but rejected. Functional behaviour is seen as emerging directly from the interaction of sensorimotor loops including the body and relevant en-vironmental features, without the need to model or encode the structure of the environment. The sense–-model–-plan–-act design strategy (encoding external features, reasoning over such encoded representations and delivering a plan into the envi-ronment) is considered a major theoretical obstacle for the design of efficient robots. The dynamical systems approach to coupled agent–-environment systems provides an alternative framework that allows one to largely replace the computational and repre-sentational frameworks.

2.2.2 Representations and enactivism

The *enactive approach* is also representation--skeptic, but not only for pragmatic reasons. Enactivism sees organ-isms as making sense of their environment by coupling precarious processes of self--organization and generation of identities (at different levels) with environmental dynamics, the latter being imbued with sense and value because of their potential effect on the maintenance of such processes. The roots of meaningful activity are located not in vehicles storing environmental information, but in coordinating dynamical processes at various scales. Internal representations—in the strong sense of internal states bearing cognitive content—are rejected by enactivism.

Therefore, within enactivism, the notion of representing, as a cognitive activity (i.e. the use of meaningful symbols), becomes some-thing that demands an explanation in itself in terms of dynamics, and not in terms of elements that are themselves already representations, thus avoiding mixing *explanans* and *explanandum*.

More-over, the enactivist conception of an organism's world (the lived and experienced environment) is not something that precedes the organism and is therefore prone to be captured or encapsulated by an agent's cognitive subsystem. It is the very constitution and activity of the agent as a whole that en-acts a world. If anything, representing is an activity that comes much later (and mostly as a social activity) in the development of cognitive skills and adaptive capacities, a form of social symboliza-tion that requires a complex repertoire of cognitive resources to come about and be properly explained (social coordination, communicative intention, creativity, etc.).

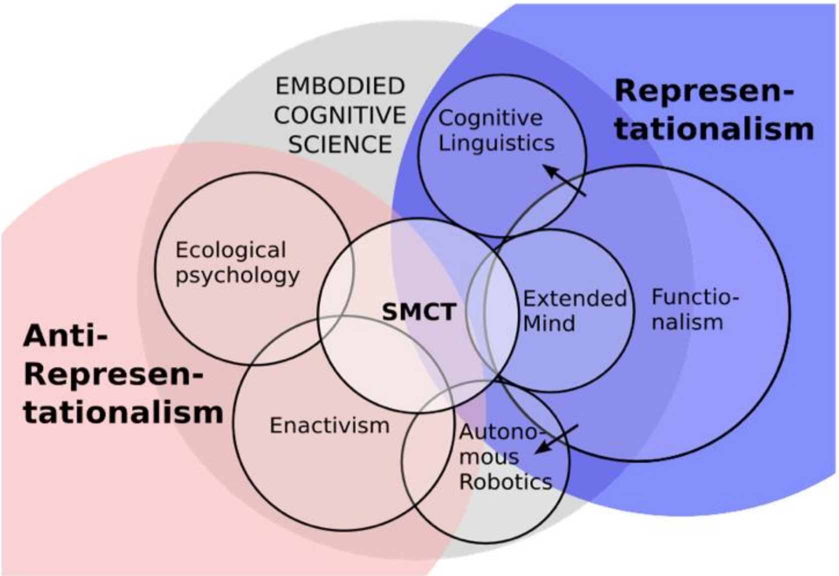

Figure 2: Map of representationalist and anti-representationalist trends among different approaches to cognitive science. See text for further explanation.

2.2.3 Representations within Sensorimotor Contingency Theory

The attitude towards representationalism im-plied in SMCT is more ambiguous. Ostensibly, SMCT claims to categorically reject the existence of internal representations. In their emphasis on the world as an outside memory, O'Regan and Noë propose that "there is no re-presentation of the world inside the brain" (O'Regan and Noë, 2001). All that is needed to explain perceptual experiences are methods for probing the pic-torial, three--dimensional world itself, i.e. the mastery of sensorimotor contingencies. In this view, SMCT presents itself as sustaining the positive claim that perceiving consists in the exercise of SMCs, and the negative claim that representations are unnecessary (in general, not just for percep-tion). However, O'Regan & Noë do accept that the visual system extracts, stores and categorizes in-formation about the environment in one form or another, and makes use of it to influence current or future behaviour. They also accept that knowledge of the laws of SMCs would need to be stored somehow. The authors are happy to label such stored information as representations (O'Regan, and Noë, 2001, p. 1017), in apparent con-flict with their claim that there are no representations of the world in the brain. However, a closer look reveals that the claim of SMCT in regard to representations is in fact not the denial of their ex-istence in general, but rather that:

1. It is not the brain's role in vision to recreate a detailed, pictorial, three-dimensional representation of the world from retinal images. We do not have such representations, nor need them to explain conscious experience.
2. To the extent that representations do exist (even if fractured, distributed, multi-level), they are neither sufficient nor necessary for seeing (and by implication for perception in general).

In support of these claims, O'Regan and Noë present the phenomenology of change blindness, per-ceptual completion, visual inversion, color perception, etc. as showing that we do not have (access to) detailed internal representations of the world. Regarding the necessity for such representations, according to SMCT we can have "flawless, unified and continuous experience" without having to build internal representations with the same qualities from the two distorted retinal images that are punctuated by blind spots and interrupted by saccades. This is because seeing does not, and cannot, consist in some part of the brain (nor mind or agent) reflecting upon an internally represented image, the suggestion of which would be committing the homuncular fallacy. Seeing is, rather, the *doing* of something in the visual modality, such as exploration of one's environment, using information avail-able to the brain. It might well be necessary that the brain extracts information from in-teractions with the environment, and abstracts this into a form that can be used across a wide range of different tasks and capacities. But such abstract multi-purpose representations are neither sufficient for nor identical to experience (which can easily be seen in the fact that having images on the retina does not make people see). What matters is how such information contributes to the sensorimotor activity of the organism as a whole. In summary, representations (or internal states) in SMCT might be necessary (an empirical matter), but certainly are not sufficient causes of perception (a conceptual matter).

3 Operational definitions

3.1 Definition of SMCs in dynamical systems terms

According to the sensorimotor approach, perception is a form of embodied know-how, constituted by lawful regularities in the sensorimotor flow, i.e. sensorimotor contingencies (SMCs), in an active and situated agent. Despite the attention that this approach has attracted, there have been few attempts to define its core concepts formally. In this section, we examine the idea of SMCs and argue that its use involves notions that need to be distinguished. We introduce four distinct kinds of SMCs, which we define operationally. These are the notions of *sensorimotor environment* (open-loop motor-induced sensory variations), *sensorimotor habitat* (closed-loop sensorimotor co-variations), *sensorimotor coordination* (reliable sensorimotor patterns playing a functional role) and *sensorimotor strategies* (normative organization of sensorimotor coordinations). We make use of a minimal dynamical model of visually guided categorization to test the explanatory value of the different kinds of SMCs. Finally, we discuss the impact of our definitions on the conceptual development and empirical as well as model-based testing of the claims of the sensorimotor approach.

3.1.1 Introduction

The sensorimotor approach to perception and experience has generated much interest and debate within cognitive science over the last decade. Its main proposal (O'Regan and Noë, 2001) concerns the sensorimotor basis of perceptual experience, hypothesising that both its content and form (what is perceived and how) are constituted by an embodied know-how of sensorimotor regularities or sensorimotor contingencies (SMCs). In working out the details of this idea, different understandings have emerged that vary in how exactly a connection is established between subpersonal sensorimotor structures and personal experience, i.e. how linkage terms such as *knowledge* or *mastery* of SMCs are to be interpreted (Hutto 2005, Clark 2006, Roberts 2009). What seems to have been overlooked in recent debates though, is the notion of SMCs itself, which we aim to remedy here.

The concept of SMCs seems to point in an unproblematic manner to regularities in the sensorimotor field: predictable or "lawful" covariations and coordinations of sensory stimulation, neural and motor activity. For instance, the projection of a horizontal line onto the surface of the retina transforms from a straight line to a curved arc as one shifts the eye's point of foveation from the line itself to points above or below it. In contrast, if the point of foveation is moved along the line, no such transformation on the retina takes place. The geometry of the viewed object, the morphology of the retina, and the particular movement pattern employed all determine the regularities in resulting patterns of sensory stimulation (O’Regan and Noë, 2001, p 941). Such regularities could in principle be described without problem, once enough detail is known about the sensory system and environment. However, this seemingly straightforward notion admits various interpretations, which impact on how the theory is to be understood and on its empirical implications. For example, what counts as a sensorimotor dependency can vary if we decide to focus on all possible sensorimotor scenarios given the details of the agent's sensory and motor systems and its surroundings, or if we focus on the regularities that are brought about by the agent's own behaviour, i.e., if we study the agent as the partial creator of such regularities, or if we consider different task-oriented scenarios with different patterns of saliency. Equally, what counts as regularity in a sensorimotor contingency can depend on the scale of observation, on whether we make purely dynamical considerations or whether the focus is on the functional organization of the task, and so on. Our goal in the following sections is to propose, clarify, operationalise and illustrate precise usages of the term SMC and associated ones, so as to render it more easily usable for empirical testing, modelling and robot design.

3.1.2 Definitions

The main idea behind the notion of SMC is that the best departure point for understanding the mind is the sensorimotor coupling between agent and environment, and specifically what is directly accessible by the agent: the sensory changes that result from the structure and dynamics of the world and from the agent's own self-generated movements. The dynamical systems approach has proved to be particularly useful for studying situated and embodied systems in which tight agent-environment coupling is an important aspect of behavioural performance. We adopt this perspective here to distinguish four different definitions of SMCs.

We start by formalising the sensorimotor coupling of an agent that senses states of its environment and whose motor variations produce displacements in space that in turn induce changes in sensory values. In general, such a system could be described by the set of differential equations shown in Figure 3 below.

Here, the environment is described by a function E that assigns changes in the value of an environmental state $\mathbf{e}$ to each position $\mathbf{p}$ in the world and takes account also of its own independent dynamics. The position vector, $\mathbf{p}$, describes in general the whole body configuration of the agent in relation to its environment. Sensors (S) transform environmental states $\mathbf{e}$ (which depend on $\mathbf{p}$), into sensory states $\mathbf{s}$ (no distinction is made at this stage between modalities), which in turn modulate the agent's internal state $\mathbf{a}$. Motor commands $\mathbf{m}$, which are a function of the internal state, activate effectors in the agent's body B that lead to changes in body configuration $\mathbf{p}$, thereby closing the loop. The sensor states, $\mathbf{s}$, will normally also be dependent on internal factors ($\mathbf{a}$) such as neural dynamics, consider the case of visual adaptation to changes in brightness. They will also depend on body configuration ($\mathbf{p}$), e.g. closing the eyelids. However, dependencies on $\mathbf{p}$ are already factored in the environmental state $\mathbf{e}$ through its dependence on $\mathbf{p}$, which include dependencies due to displacements of the body as well as active changes introduced in the environment by the agent.

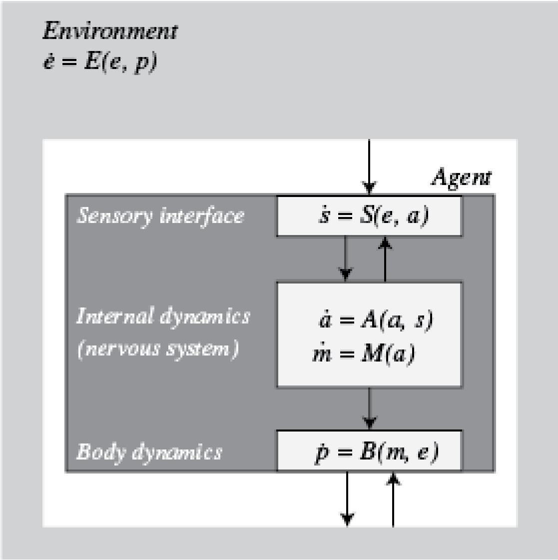

Figure 3: Agent-environment coupling. The world is partitioned into components describing the dynamics of the environment, the agent and their interaction. The agent's body is further subdivided into sensory and motor interfaces as well as its "nervous system".

While details of these equations might vary depending on the specific model under consideration, the important point is that for every coupled agent-environment system we can choose to identify some variables as describing the environment and some as describing the agent. Within the agent we can further choose to distinguish between the sensory and motor interfaces on the one hand, and its internal state on the other. Again, depending on the particular interest, different distinctions can be made. For example, while in some cases one might consider individual photoreceptors to be the sensory interface and other retinal cells (e.g. the retinal ganglion cells) to be the internal state, in other cases one might consider the retina as a whole as a sensory interface, and only neurons further upstream as internal variables. What is crucial, however, is that independent of how one chooses to partition the whole system into interacting components of environment and agent, sensorimotor interfaces and internal state, the following four sensorimotor structures can always be identified.

3.1.2.1 Sensorimotor environment

First, one can describe how an agent's sensor values **s** change in relation to all possible motor states, i.e. assuming that the motor command **m** varies freely. It corresponds to opening the sensorimotor loop by removing the equation $\mathbf{m}' = M(\mathbf{a})$, thus making **m** a free independent variable, decoupled from the agent's internal state **a**. This relation can depend on several environmental and bodily factors – for instance, the position **p**, considered a parameter in this open-loop version of the model – which for simplicity we put together in a vector **q**. In the most general terms, this is expressed as an implicit function, which may be time-dependent, involving sensor and motor values: $f(\mathbf{s}, \mathbf{m}, \mathbf{q}, \mathbf{t}) = 0$, where **m** is the independent variable. In some cases, this relation can be expressed explicitly as $\mathbf{s} = g(\mathbf{m}, \mathbf{q}, \mathbf{t})$. Mathematically, relevant aspects of this relationship could be captured, when possible and at least locally, by the partial derivative $\partial \mathbf{s}/\partial \mathbf{m}$, i.e., the change in sensor values $\mathbf{s}$ resulting from changes in the independent variable $\mathbf{m}$ while all other variables are held constant.

We call this functional relation (f or g) the *sensorimotor environment*, which is specific to any agent that shares the same sensorimotor embodiment and external environment, but is independent of the agent's internal state and the actual succession of actions it would perform in the given environment. We call this the SM environment because it constitutes the set of all possible sensory dependencies on motor states ($\mathbf{s}$, $\mathbf{m}$) for a particular type of agent and environment. Whatever specific behaviour the agent exhibits, its sensorimotor projections will always be found within this set. Generally, the SM environment will have properties of smoothness, dimensionality, and symmetry that constitute the most general constraints to any actual sensorimotor trajectory for a given agent, including both successful and unsuccessful sensorimotor strategies for solving a given task. The properties of the SM environment are the most general kind of regularities or what we consider "laws" of SMCs. They are shared by all agents with the same bodies in a given environment.

3.1.2.2 Sensorimotor habitat

For a different conception of SMCs we can identify regularities that have to do with how an agent actually 'navigates' the SM environment. Here we close the loop again and take into account the agent's internal state and its influence on the effectors. We define the sensorimotor habitat as the set of all sensorimotor trajectories that can be generated by the closed loop system, i.e., taking into account the evolution of the internal states $\mathbf{a}$. This structure describes how an agent actually "moves" within the SM environment, the different instantaneous tendencies, the regions that are most likely to be visited, and other regularities. The SM habitat inherits some constraints from the SM environment (e.g., relations of symmetry), but it is likely to be of a higher dimensionality because of the addition of internal dynamics. In other words, although the SM environment constrains the possible habitats, there are still an infinite number of ways in which the SM environment can be 'inhabited'.

Formally, the SM habitat corresponds to the set of actual sensorimotor trajectories travelled by the closed-loop system (equations 1–5) for a range of values of relevant parameters (initial positions, initial states, environmental parameters, etc.). Whenever possible, local information about the SM habitat could be captured by the total derivative $\mathrm{d}\mathbf{s}/\mathrm{d}\mathbf{m}$ where $\mathbf{m}$ is not any more a free or independent variable, but is constrained by the agent's internal states, $\mathbf{a}$, and, needless to say, the coupling of the agent with its environment. As is the case with the SM environment, the SM habitat will have certain properties of smoothness, dimensionality, topology, attractors and symmetries that characterise a particular type of agent and its environment. These regularities specify SMCs that take into account the active engagement of agent and environment.

It is important to note that neither the SM habitat, nor its properties, can in principle be deduced from the SM environment. It is true that whatever the SM habitat, its existence must be a possibility in the SM environment. And in specific cases properties of the former might reflect properties of the latter. But the agent's internal dynamics also create completely new behavioural constraints and new ways in which sensors and motor can be coupled. In other words, the "laws" of SMCs of the SM environment may constrain but not fully determine the regularities of SMCs of the SM habitat.

3.1.2.3 Sensorimotor coordination

So far we have been considering the agent in its environment as a dynamical system but outside of any functional context (such as achieving a certain cognitive performance, maintaining its viability, and so on). Within the SM habitat we may find certain regularities as we have said. Some patterns may be repeated for a large set of parameter values, there may be (meta)stable trajectories, and even transients may occur reliably for a set of circumstances. According to usage in the area of autonomous robotics (Pfeifer and Scheier, 1997; Beer, 2003), we call any of such reliable or (meta)stable pattern a *sensorimotor coordination*, only if it can be shown to contribute functionally to the performance or goals of the agent. For example, in the now classical example, the softness of a sponge can be determined by squeezing it between the fingers (Myin, 2003), the quality of interest resulting from a specific correlation between applied pressure and felt resistance. We consider this a SM coordination, i.e., a SMC described by co-dependencies between **s** and **m** that reliably contributes to functionality.

SM coordination patterns are characterized by a significantly lower dimensionality than the SM habitat – they are specific, often local sensorimotor co-dependencies that are dynamically organised in time – but they are not necessarily always (meta)stable. Even transients, as long as they are 'used' reliably, could be explanatorily linked to functionality and so count as SM coordinations. In practical terms, an SM coordination pattern is determined by a dynamical analysis of the agent within the context of a given task or performance. It will inherit dynamical constraints from the SM environment and the SM habitat and in general some of the most likely candidates will come from regularities in the SM habitat. However, not all regular patterns in the SM habitat will necessarily be SM coordinations, as some of them may not have any functional significance.

3.1.2.4 Sensorimotor strategy

Until now we have described different types of sensorimotor structures in terms of their dynamical properties and in terms of their functional contribution, but without reference to any normative or adaptive dimension (i.e., the scales that allow for different measures of efficiency, reliability or level of skill). The explanatory value of the sensorimotor approach is, however, often expressed in normative terms such as "being attuned to SMCs" or "skillful mastery of the relevant laws of SMCs". A normative framework involves reference to a given criteria or norm, which distinguishes or values some possible outcomes or courses of action above others: a dexterous movement vs. a clumsy disaster, achieved know-how vs. lack of experience, attunement vs. dissonance, and so on. We are not going to discuss the origins of such norms here, we will just assume that they exist and that one can quantify them or provide some kind of normative gradation, such as efficiency, fitness, optimality or even subjective criteria like its hedonic value, and so on.

A complex task will require various SM coordination patterns, spread out in time, sometimes in sequential order, sometimes in parallel, and involving different action and perceptual systems. Even if several such combinations may be efficacious, some may be more efficient than others. Within a normative framework we can introduce the notion of a *sensorimotor strategy*. The idea describes an organization of SM coordination patterns that is regularly used by the agent because it has been judged as better or preferable (along any relevant normative framework) for achieving a particular goal or because it has plastically pre-disposed the agent to re-use the same patterns (forming a habit). The development or acquisition of a sensorimotor strategy describes how an agent becomes attuned to a specific environmental situation, by selecting, modulating or entraining SM coordination patterns in accordance with that goal and relevant norms. The notion corresponds to an even more agent-centred and history dependent idea of SMCs and it seems close to some of the uses of the term that link SMCs and personal level phenomena.

Table 1 presents a summary of our categorisation of sensorimotor structures with respect to their dependency on environmental and agential factors.

Defined by or depends on	Environment	Embodiment	Internal dynamics	Task	Normative Framework
SM environment	✓	✓			
SM habitat	✓	✓	✓		
SM coordination	✓	✓	✓	✓	
SM strategy	✓	✓	✓	✓	✓

Table 1: Categorisation of sensorimotor structures with respect to their dependency on environmental and agential factors.

3.1.3 Example application in a minimal model

In this section we use a minimal model to illustrate the different kinds of SMCs proposed and to try identify the roles they play in the behaviour of an agent engaged in a task. The aim is not only to illustrate their use but also to show their operational and explanatory value. The model is deliberately simple but not trivial, following the tradition of minimal cognition models inaugurated by Randall Beer (1997, 2003) and others (Cliff, 1991; Harvey et al., 1996). Specifically, we consider a minimal model of visually guided categorization that allows us to illustrate and analyze in detail the agent's sensorimotor dynamics.

The agent in question is situated and can move left and right in a one-dimensional toroidal environment (see Figure 4). The environment extends over 1 (arbitrary) unit in space, and the agent's maximum velocity is 1 unit/s. Within this environment, the agent is presented with visual stimuli in the form of two bell shaped peaks (Gaussian functions) of different widths w (0.03 and 0.08), defined by the equation

$$E(p) = he^{-\frac{(p-x)^2}{2w^2}}$$

where h is the height of the shape, x the position of its peak and ±w corresponds to the maxima of the functions derivative, i.e., to the inflection points where its slope is steepest.

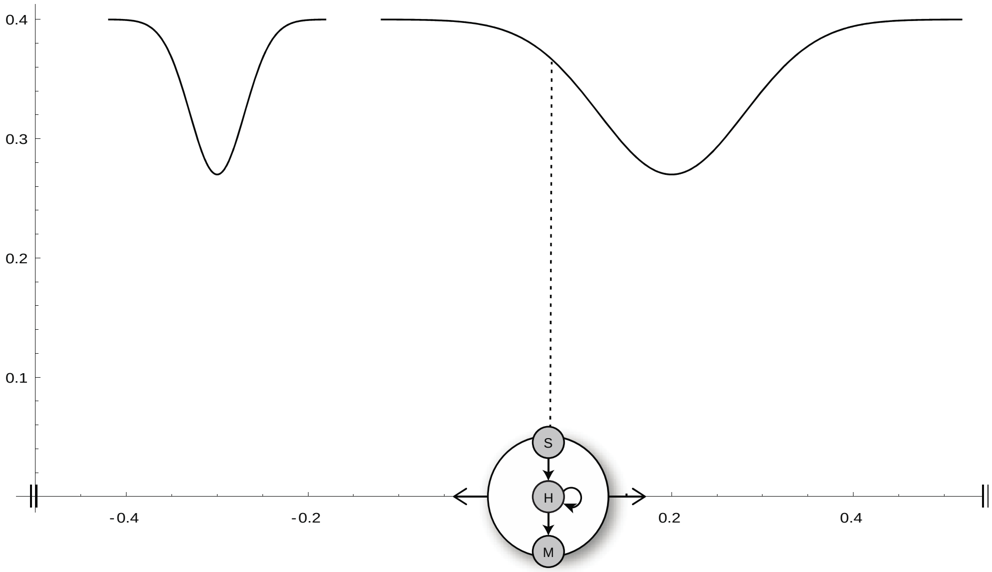

Figure 4: Minimal agent and its circular (wrap-around) 1-D environment (horizontal axis). The agent possesses a sensor (S) that measures the distance to objects in front of it (narrow or wide Gaussian shapes), and feeds into a set of hidden neurons (H) of the agent's neural network. The hidden neurons in turn are recurrently connected to themselves and drive the motor neuron M controlling the agent's horizontal velocity.

From trial to trial the two shapes are presented in random horizontal positions with a minimum guaranteed separation. They also vary in height (0.13 ± 50%), but such that within each trial their height is equal. The only features distinguishing the two shapes in each trial, therefore, are their steepness and horizontal extent. The agent senses the shapes in the environment via a distance sensor whose activity increases proportionally to the proximity of the object directly in front of it. The task to be solved by the agent is the discrimination between wide and narrow shapes, requiring it to move away from the former while maintaining itself as close as possible to the peak of the latter. It is the continuous formulation of a discrete task presented in Maye and Engel (2011), where a Bayesian approach was used to learn the sensory effects of the agent's motor commands. The situation is somewhat similar to a blind person exploring different shapes with the help of a cane only. Since the shapes' height can vary, it is clear from the setup that no instantaneous sensory input can bear enough information to discriminate one shape from the other, but that an active sensorimotor strategy is needed instead.

The controller of the agent consists of a small 2-node continuous-time, recurrent neural network (CTRNN). Each node in this network is governed by the differential equation

$$\tau \dot{y}_i = -y_i + \sum_{j=1}^{n} w_{ji}\sigma(y_j + \theta_j)$$

where y_i is the activation of node i, its time constant, w_{ji} the strength of the connection from node i to node j, θ_j a bias term, and the logistic (sigmoid) activation function. One of the nodes (H in Figure 4) receives as input the time derivative of sensor-reading S. A different node (M) delivers continuous motor commands. Its output is remapped to the range [-1, 1] and specifies directly the velocity of the agent (to the left or to the right depending on the sign).

We artificially evolved the neural controller so as to be able to solve the discrimination task (moving away from wide shapes and approaching narrow ones). The parameters of the agent's neural controller were found using a microbial genetic algorithm (Harvey, 2011), with mutation as a random offset vector in the unit hypersphere (vector length chosen from a Gaussian distribution, and direction from a uniform distribution). The fitness function measured the root-mean-square error between the position of the agent and the narrow shape's peak, averaged over the last two seconds of each 10s trial. An individual's overall fitness was then averaged again over 100 trials of random shape presentations.

The agent was easily evolved for the task and successful solutions could discriminate shapes across a whole range of widths (exhibiting generalisation). The resulting discrimination behaviour consisted of two distinguishable types of agent-environment interactions. In the case of narrow shapes the agent approaches at constant velocity but starts oscillating once in contact with the shape. This oscillation is asymmetric, and such that the agent slowly approaches the peak, close to which it ultimately settles with decreased oscillation amplitude. For wider shapes, the initial approach is identical. But instead of moving in a cyclical fashion up the slope, the agent moves away from it. In the following sections we identify the sensorimotor structures introduced above for this agent, and ask what they can tell us about its behaviour.

3.1.3.1 Sensorimotor environment

The sensorimotor environment, to recapitulate, captures properties of the external environment and the agent's sensorimotor interface, without taking into account the agent's internal structure or dynamics.

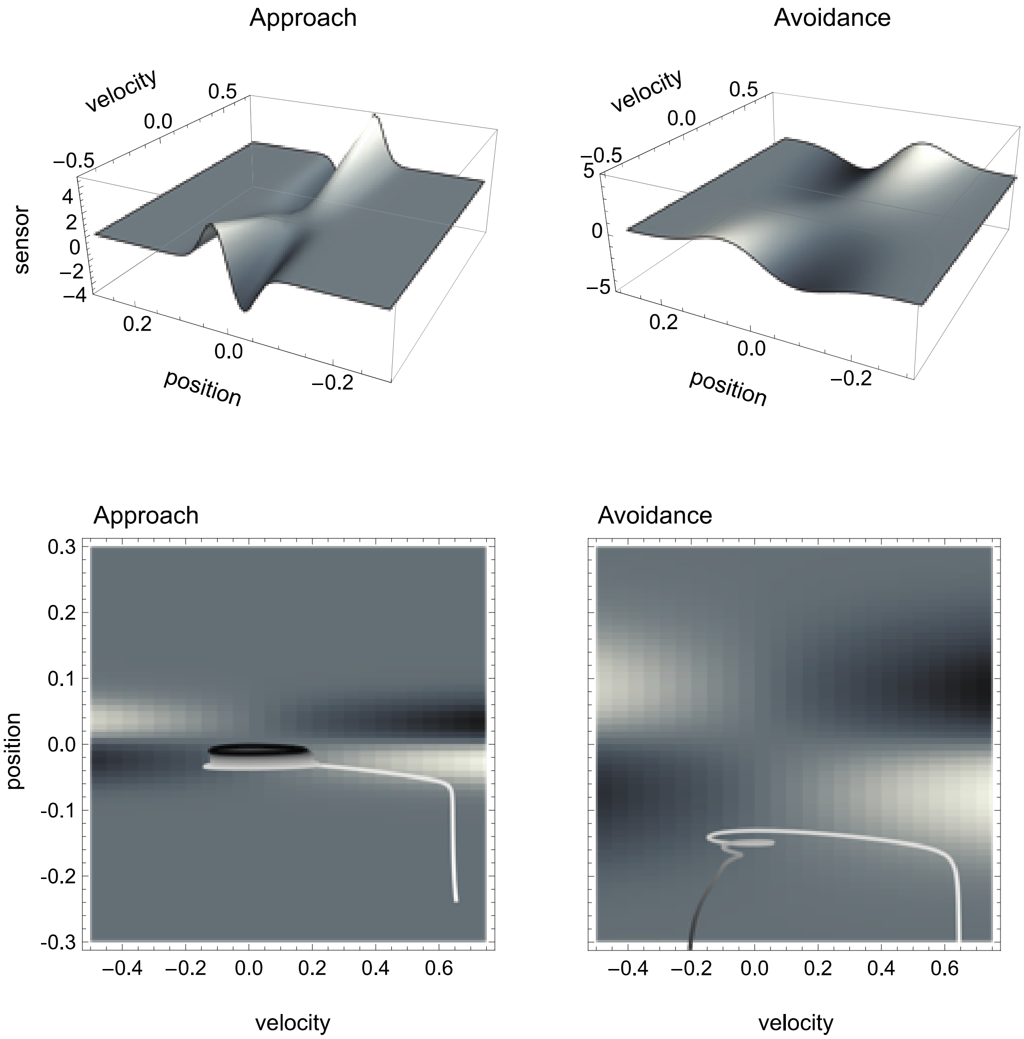

Figure 5: SM environment for approach of narrow and avoidance of wide shapes. Plotted is the sensory activation that results from issuing a motor command that determines agent velocity at a given position. Top row: In the shape of the surfaces one can easily identify the derivative of the Gaussian gradients present in the environment. The amplitude of this derivative varies with agent velocity, reflecting the working of the agent's sensor, which is proportional to the time-derivative of the sensed distance and therefore dependent on the agent's speed of movement. Bottom row: actual trajectories (varying from white to black as time progresses) overlaid on a 2d representation of the SM environment.

In Figure 5, we have plotted this relationship as the sensory values that result from the agent being located at a certain position (relative to the centre of the peak) and issuing a certain motor command (moving at a certain speed). Since the agent senses the time derivative of the height of the gradient at its current position, a specific sensor value is produced for each position and velocity of the agent. The resulting surfaces for the two environments represent the agent's SM environment in that they capture the functional relation between **s** and **m**, i.e. the sensory consequence of performing an action (moving at velocity v) taking position p as a parameter (**q** = p).

What are the regularities of this surface (its "laws" of SMCs), and how do they contribute to explaining the agent's behaviour? It is clear that there are two types of symmetries in the sensorimotor environment: those reflecting properties of the external environment, i.e. the bell shapes, and those reflecting the agent's motor abilities, i.e., the fact that the agent can move equally in both positive and negative directions. As a result, we observe that sensor values as a function of position and velocity observe the symmetry S(p,v) = S(-p,-v). The surface also reflects other general properties of the sensorimotor coupling, such as the fact that sensor activity is continuous and smooth.

The structure of the SM environment, in this case for example its symmetry, can constrain but does not fully determine the possible behavioural strategies to solve the task. Based on the symmetries of the SM environment we can for example formulate the following prediction: if we invert the motor signal (effectively exchanging the left/right directions) we should observe the same discrimination behaviour, with the difference that the agent will "scan" the shapes on the opposite side of the peak. We have carried out the experiment and the hypothesis was indeed confirmed.

The SM environment on its own cannot, however, provide a full explanation of how the agent achieves the distinction between shallow and steep gradients. If we look at the agent's actual trajectories in the two sensorimotor environments (top view in Figure 5), we can at best come up with heuristic descriptions of the agent's behaviour that seem to involve different types of oscillation between negative and positive sensory regions. But there is no obvious interpretation at the level of the SM environment of why the agent follows these particular trajectories.

3.1.3.2 Sensorimotor habitat

The sensorimotor habitat, according to our definition, describes the relationship between sensor activity and motor commands but taking into account the internal dynamics of the agent. It is the set of all possible trajectories given the constraints of the agent's internal dynamics, in other words, the bundle of actual sensorimotor trajectories that the agent takes given a range of starting conditions and parameters. If we are dealing with a potentially complex, non-linear dynamical agent-environment system, providing a full analytical description of this set might be practically infeasible or theoretically impossible. One can however adopt a quasi-static method, which can also apply to those systems that are in principle too complicated to solve analytically. The idea here is to treat the variable that links two components of a complex dynamical system, such as the sensor variable in our model, as a fixed parameter. This removes time-dependency from the dynamical component of interest, and allows one to calculate its qualitative behaviour (limits sets, attractor basins etc.) for the given, now fixed, parameter. In a next step one can then study how the qualitative behaviour changes as the parameter is varied (bifurcation analysis). Together, these two analyses describe how the overall behaviour of the component results from the change in its qualitative dynamics as the normally time-dependent input is varied.

In figure 6 we show the result of carrying out such analysis for our model agent, i.e. the qualitative behaviour of the agent for different values of its sensory input. Here, we have determined for each fixed sensor value (which is given by the surface of the SM environment as a function of position and motor command), the steady-state of all the agent's variables, i.e. the state to which the agent would ultimately converge if given enough time (the attractors). Of these states, we have plotted only the coordinate of the motor command here, as this ultimately drives the agent's behaviour.

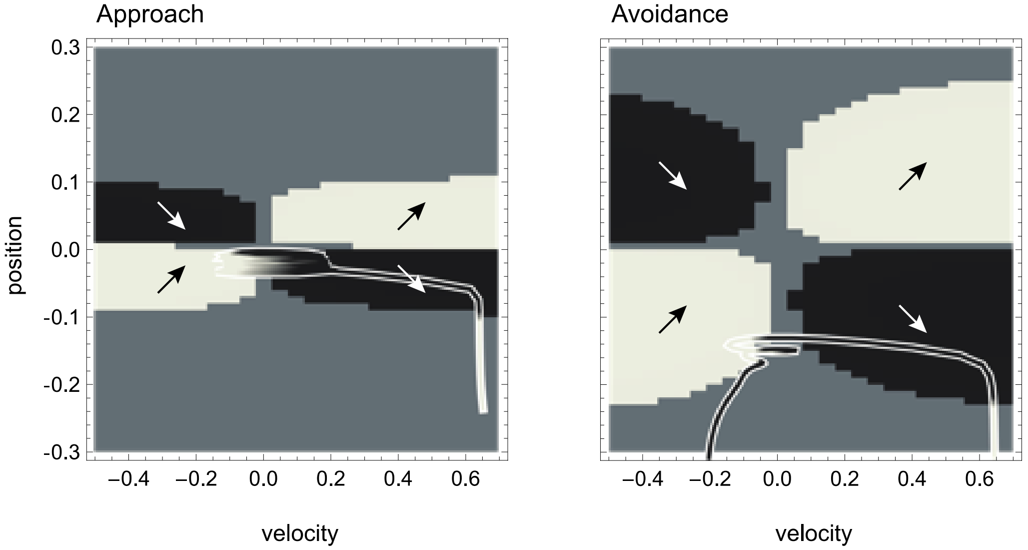

Figure 6: Attractor landscape of evolved agent in approach and avoidance conditions. Plotted here is the steady-state motor output as a function of fixed sensory input resulting from a given motor command (velocity) at a given position. Black attractor regions correspond to negative and white regions to positive steady-state velocities (0.6 and -0.2 respectively). Gray areas indicate bi-stable regimes. Actual trajectories are overlaid and colour-coded according to the attractor the agent moves toward at any given time. Arrows indicate approximate tendencies of state change for the different attractor regions. Compare to previous figure of SM environment, which is plotted on the same axes.

Comparing with the SM environment (Figure 5), we can see that the agent's internal structure transforms the four smooth peaks and troughs of the sensorimotor environment into four discrete regions of attraction. The white regions here correspond to positive velocity attractors ($v \approx 0.6$), and the black ones to negative velocity attractors ($v \approx -0.2$). Additionally, in some regions the system is bi-stable (gray). In this area, which attractor the system tends towards depends on the agent's internal state at the given time.

Now, what are the salient regularities of this attractor landscape? Firstly, it reflects the same symmetries as the sensorimotor environment above, one due to the environment the other due to the agent's motor capabilities. It should be noted that this is not by necessity. In theory, the SM habitat could be shaped in a way that is unrelated to the SM environment. The agent could, for example, choose to disregard sensory input completely, in which case the peaks of the bell shapes would not be reflected in the SM habitat. However, the requirements of the task here have led the agent (via the evolutionary algorithm) to preserve in its internal dynamics those features of the environment that are necessary for achieving the task.

Secondly, the attractor landscape implements a binary choice. Depending on whether the sensory values are above or below a certain value, the system will tend to move in either one or the other direction (indicated by arrows in Figure 6). One prediction we can make based on this structure is that since there is no attractor that would lead to zero velocity, the only way the agent can stay close to a peak is by using changing sensory inputs to oscillate back and forth between different attractors. This is of course the observed behaviour. Looking at the agent's trajectories within this attractor landscape, one can also explain the difference between the approach and avoidance behaviours. Even though the steady-state motor outputs are identical in both types of environment, the regions in which they can be found differ in size (left and right plots in Figure 6). This leads to a situation where the initial approach of the agent towards the shape is similar in shape. But when faced with wider shapes this trajectory does not carry the agent as far through the attractor region as it does for narrow shapes. Therefore, when the agent leaves the initial attractor region, it manages to enter into an asymmetric cycle of transitions between the two attractors in one case (approach), but gets fully captured by one of the attractors in the other (avoidance).

From a higher-level perspective we can therefore say that the agent's attunement to the environment and task at hand is dependent on its internal structure. It is the attractor landscape, which transforms the sensorimotor environment into actions that conform to the (in this case externally enforced) achievement of the task. It is also the attractor landscape, itself modulated by sensory perturbations, that determines which areas of the sensorimotor environment the agent will visit and how, in other words, what we have defined as the sensorimotor habitat: for every sensory perturbation this landscape provides information about which action the agent will take, and therefore what the following sensory stimulation will be as a consequence.

3.1.3.3 Sensorimotor coordination

Finally, we illustrate what we call the sensorimotor coordination pattern in our model agent. Figure 7 (left) shows a convergence to a lower dimensional pattern in sensorimotor rates of change for the case of approaching behaviour. This stable lower dimensional pattern is evidence of a mutual, closed-loop influence between sensory and motor variables. In other words, this is evidence that motor variables not only determine sensory patterns, but themselves are not independent variables. The fact is plainly visible and obvious in this model, but it remains conceptually crucial in wider discussions of the sensorimotor approach where often no mention is made of what determines the motor patterns that affect perception in the first place.

The particular SM coordination pattern also reinforces a functional relation to the environmental object, in this case, the behaviour of staying close to the peak performing an oscillatory scanning motion. For avoidance (Figure 7 right) this is not the case, as no stable sensorimotor pattern in relation to the object is required, just its avoidance. However, according to our definition, and the fact that this transient behaviour obtains reliably in the presence of wider peaks and that it results in a behaviour that contributes to the desired function, this also counts as a case of SM coordination.

For a pattern to count as SM coordination the convergence to a (meta-)stable lower dimensional dynamics or its reliability in general is necessary but not sufficient. As illustrated in this case, it is also necessary for this pattern to be functional to the task. In our simple model, the functionality is achieved by establishing a pattern of small oscillations on a particular zone of the object (the right hand side of the narrow peak) using stable oscillations and not establishing any stable pattern when the gradient indicates the presence of the wider peak, using a reliable transient.

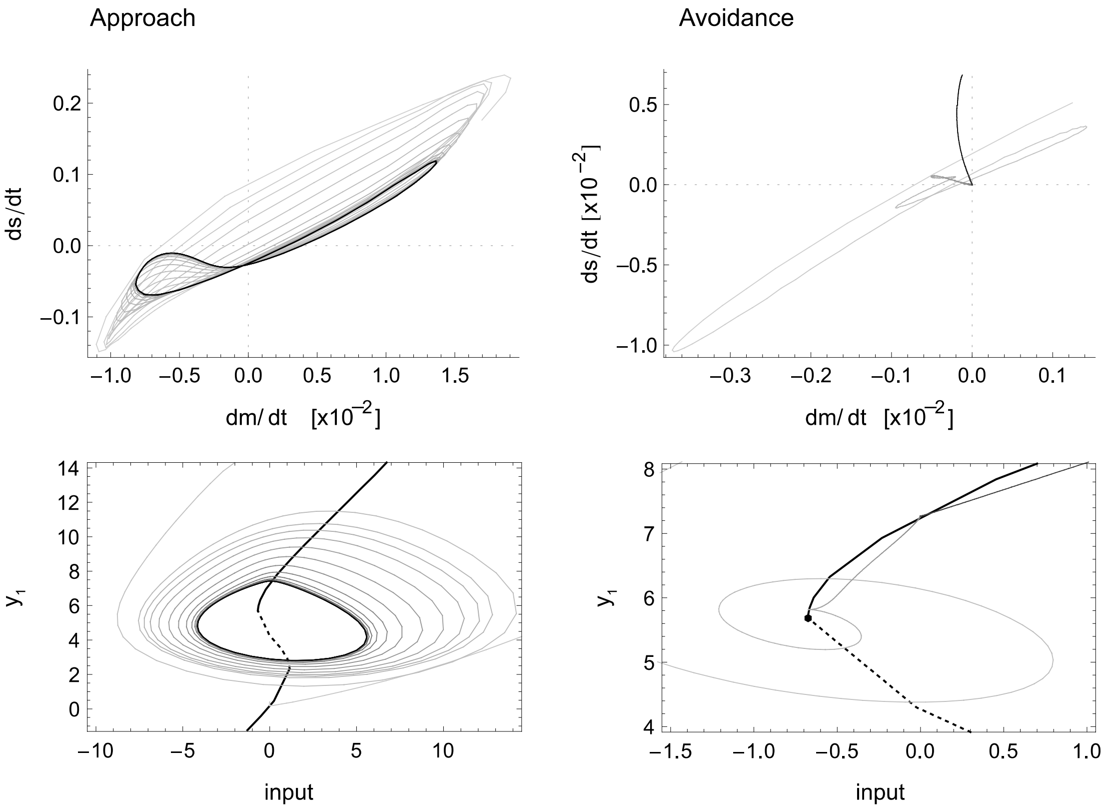

Figure 7: Sensorimotor coordination patterns for approach condition (left) and avoidance (right). Top row: change in sensory activation (ds/dt) as a function of change in motor commands (dm/dt) during the agent's interaction with the bell shape. Bottom row: the same coordination patterns as trajectories in the hidden neuron's bifurcation diagram, i.e. in coordinates of sensory input and hidden neuron activation y_1.

Another important aspect concerning sensorimotor coordination patterns is illustrated in the bottom row of Figure 7. This is the fact that SM patterns do not correspond to or are determined solely by endogenous “brain” dynamics. As can be seen in the case of approach (left), the stable neural pattern cannot be trivially deduced from features in the agent’s internal state space (limit sets) or changes therein (bifurcations). Rather, what happens here is that the agent’s state is always “chasing” one attractor or the other, without ever being captured. Because the agent’s sensory input changes as a result of his movements (on the same time scale as the behaviour), so does the steady state the agent tends to. In other words, the agent is always on a transient towards an attractor that is never stationary. Interestingly though, the overall pattern that emerges forms a stable oscillation, which likely corresponds to a limit cycle of the coupled agent-environment system. The environment therefore plays as much a part in the creation of the observed SM coordination pattern as the agent’s internal dynamics.

3.1.3.4 Summary

In summary, the different sensorimotor concepts we have introduced contribute to a full explanation of the observed behaviour of our model system. SM coordination patterns determine a relation between lower dimensional (meta)stable or reliable trajectories in sensorimotor dynamics and their contributions to task functionality. The SM habitat establishes the “rules” that explain the presence of SM coordination by examining the dynamics of the coupled internal and environmental variables. And the SM environment establishes the wider constraints to the SM habitat such as symmetries that depend solely on the environmental and embodiment structures.

The simplicity of the task we have used in this model does not permit an easy illustration of the concept of sensorimotor strategy. We believe the model could be modified in relatively straightforward ways to this effect, but the more complex analysis would be less effective for illustration purposes. A SM strategy entails the skilful use and selection of various possible SM coordination patterns according to goals and norms. We can again imagine a more complex scenario involving more shapes and more actions with a many-to-one viable or desirable relation. Wider norms (e.g., energy efficiency) or more general longer-term goals would help determine what action to perform on a given object. We expect this process to happen at higher levels of dynamical modulation. If the environment is not altered by the agent, or if its own embodiment remains unchanged, then the only possibility for this higher level modulation to happen, since the SM environment will remain the same, is at the level of the SM habitat (because this level also depends on internal variables). A model that illustrates this possibility is presented in (Iizuka and Di Paolo, 2007). In more complex cases, where aspects of the embodiment can be directly manipulated or the environment is itself modified by the actions of the agent, the modulation that permits the choice of SM strategies can also happen at the level of the SM environment. It is in these two kinds of situation that we can speak of agency in its proper sense (Barandiaran, Di Paolo and Rohde, 2009), i.e., the normative regulation of the coupling between the agent and the world.

3.1.4 Discussion

We would now like to reflect on some implications of the four kinds of SMCs we have identified. We will focus here on the role of action and on some implications for the question of whether mastery of the laws of SMCs should necessarily be interpreted in a representational sense. More open-ended implications related to agency and temporality are discussed in Section 5.

The definitions of the SM structures highlight the relevance of the determinants of action, a question that has been rather absent in the sensorimotor approach. Except for the SM environment, which describes a dependency of sensory activity on motor changes, the other kinds of SMCs are strictly speaking sensorimotor co-dependencies, as the sensorimotor loop is closed. Sensorimotor theory has been formulated in terms of SMCs, but, lacking a definition, the latter have been almost exclusively illustrated as strict sensory dependencies on motor action. We should note that action has been treated more or less as a free variable in these illustrations. By this we mean that the appropriate action in a perceptual context is brought into an explanation of perception as required and without constraint. The squeezing movement of the fingers constitutes in part the softness of the sponge and the stroking movement of the hand constitutes the smoothness of the table surface. But what calls forth these particular movements in each case, why don't we stroke the sponge and squeeze the table? In each case what counts as appropriate action is in part also constituted by the perceptual context – i.e., action is perceptually constituted – and this aspect has been underdeveloped in sensorimotor theory. Except for SM environment, the other kinds of SMCs change this situation at the most basic level by including closed-loop dynamics. The difference between SMCs as dependence of sensory activity on motor changes, and SMCs as mutual co-dependence is illustrated in the following equations:

$$\mathrm{M} \rightarrow \mathrm{S}: \quad \Delta \mathrm{S} = SMC(\Delta \mathrm{M}) \quad \text{Sensorimotor dependence}$$

$$\mathrm{M} \circlearrowleft \mathrm{S}: \quad SMC = \mathrm{F}(\Delta \mathrm{S}, \Delta \mathrm{M}) \quad \text{Sensorimotor } \textbf{co}\text{-dependence}$$

where S stands for sensory and M for motor states or changes. Here the first notion of SMC, with its emphasis on how perception is influenced by actions, corresponds to frequent use in the original literature, but only the second one properly describes the structure of sensorimotor co-variations in a closed-loop system.

Can the four kinds of SMCs throw light on some of the questions we raised at the beginning of this section? We think that at least at this stage they can contribute by clarifying the terms of ongoing debates such as the nature of the linkage between subpersonal and personal phenomena, i.e., between SMCs and perception. As we have mentioned, phrases like "mastery of the laws of SMCs" have been given various, sometimes conflicting, interpretations. The original authors, for example, suggest that mastery consists in the acquisition of knowledge at the personal level (accessible to action planning) about the nature of subpersonal processes (SMCs), for instance the knowledge that the projection of a stationary object on the retina would move one way when moving one's eyes to the left, and the other way when moving to the right (O'Regan and Noë

2001, p. 949). Now, some argue that the notion of knowledge in SMC theory should be abandoned, in favour of the idea that the enactment of SMCs themselves suffices to account for the qualitative differences (between objects, modalities) in perceptual experiences (Hutto, 2005). Others emphasise that perceptual experience in the absence of overt movement can only be explained by reference to the deployment of acquired knowledge (Roberts, 2009). However the problem with this latter interpretation (which certainly seems closer to the original formulation of SMCT) is the precise role of know-how, or mastery of sensorimotor regularities, that is not being actualised at a given time. How could these potential regularities (e.g., the expectation that the rear part of a solid object is also solid were we to walk around it) inform, let alone constitute, our current perception?

While not fully answering this question, the use of the four kinds of SMCs in explaining the behaviour of our evolved agent may throw some light on this issue. As our analysis has demonstrated, the behaviour of the agent cannot be predicted from the environment or the sensorimotor embodiment alone, but is the result of a coupling between internal processes and sensorimotor dynamics. This attunement is what transforms environmental and sensorimotor regularities into action tendencies and their sensory consequences. Crucially, there is nothing in the internal dynamics of the agent's "brain" that represents the SMCs that are being enacted or, for that matter, the sensorimotor regularities that are not actualised but may still have a dynamical influence (see our analysis, e.g. Figure 7). These regularities in the dynamical landscape certainly exist and have a role in the production of behaviour, but they are not represented by the agent in any way.

The analysis of how trajectories are actually formed due to the regularities in the SM habitat and how the SM coordination patterns produce the desired result point to the fact that the question of direct access vs. represented knowledge may rely on false assumptions. These assumptions seem to be: 1) Only what happens here and now can be accessed directly. 2) Anything that is accessed about what happens not-here and not-now, must be somehow "brought" into the here-and-now via representations. Our model shows that there is a third possibility, or perhaps that the first possibility should be interpreted in terms of a "thick" here-and-now, that is, not only the states that are actualised at a given moment, but also the virtual tendencies entailed by them. As we have seen, strong tendencies defined in the SM habitat heavily constrain the actual trajectories of the agent (Figure 6). As such, these trajectories may be said to directly bear "information" about the regional (non-local) dynamical sensorimotor structure. Such information may well only be probabilistic rather than certain, but it is directly available as virtual tendencies entailed by the current states. To give a familiar case that makes these points concrete, we are able to perceive the slope of the ground with our eyes closed even if we're standing still on it; this local slope both constrains our actions and gives us information about the nearby state of the environment.

As such, mastery of the laws of SMCs does not necessarily imply the deployment of representational knowledge to deal with non-actualised sensorimotor regularities. Mastery, on the contrary, would be a measure of how accurately an agent can read the entailed virtual tendencies in the thick here-and-now.

3.2 Sensorimotor Contingencies as Probability Distributions

In a complementary theoretical approach, also developed within the eSMCs project, Maye and Engel (2011; 2012a: 2012b) have developed an analysis of SMCs as fundamentally probabilistic: for a given action, given sensory results are more or less likely. Thus, a probability distribution over action-outcome pairs is one way of capturing the current SM landscape in which the agent finds itself. This probabilistic approach has been developed via the definition, and successful implementation, of a specific computational and mathematical control framework, in the context of robotics applications.

The specific implementation of the probabilistic approach to SMCs developed by Maye and Engel involves discrete-time h^{th} order Markov models, where h is the history length which the robot is considering[2]. The robot then generates action commands (initially according to some heuristic developed by the robot designer) and records the sensory consequences. It turns out that for a real (or simulated) simple embodied robot, only a fairly small percentage of the action-outcome (ao) space is encountered. Therefore, the robot is pretty soon in a position to be able to estimate the probabilities of action-outcome pairs, based on the frequencies with which these have been observed in the past. In order to generate actions appropriate to a given task, the robot also needs some form of evaluation function. In this case simple evaluation functions are hard-wired into the robot, e.g. the robot may be 'punished' for tumbling (falling over), or for hitting anything with its bumper. Given this setup (essentially, a profit-loss function and a probability distribution) it is possible to choose a next action, which maximizes the expected reward. Depending on the history length used, this probabilistic evaluation may only depend on the previous timestep, or it may depend on a history several steps in length.

Various successful implementations of this idea have already been produced. For instance, in a discretized version of the object-discrimination task analyzed operationally above, it has been demonstrated that a simple simulated robot can easily be trained to learn the difference between, say, a 'spike' and a 'block' (narrow and broad objects), and to track one but not the other (Maye and Engel, 2011). Equally, in both a simulated and real robot platform, it was possible to train the robot to move within its arena, whilst avoiding the arena walls (Maye and Engel, 2012a). Finally, in a both a real and a simulated Puppy robot (i.e. using four legged locomotion) the robot was able to learn which of several possible gait patterns was most stable, on various different surface materials, and to adopt the gait (or pattern of gaits) which gave it the greatest overall stability

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[2] In the specific implementations tested so far, the input and output of the robot was reduced to a few bits each. Conceptually, the approach can be scaled up, but for reasons of tractability, and as proof of concept, it is interesting to show that useful, competent examples of minimal cognition can be demonstrated even in a relatively low-bitrate implementation.

(Hoffman et al., 2012). It should be noted that in all cases, the parameter of interest (e.g., what the supporting surface was; whether the robot was near or far from a wall) could not (even in principle) be read off directly from any sensor, but rather was implicit in the patterns of sensorimotor interaction. Using this probabilistic model, with appropriate hardwired evaluative functions (e.g. avoid tumbling; avoid bumper contact) the real and simulated robots were easily able to learn these probabilistic environmental and proprioceptive sensorimotor contingencies, and to achieve real-world tasks.

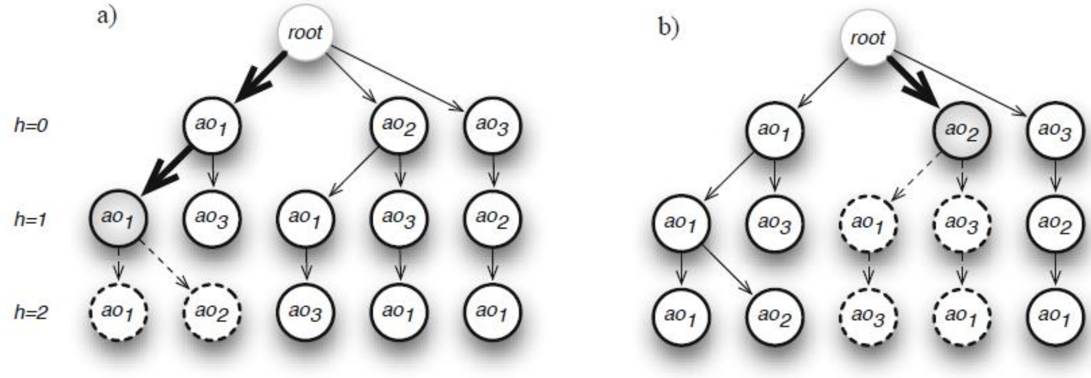

Figure 8 a) Predicting future sensorimotor events by remembering previous sequences. Suppose the agent has experienced the sequence of events *ao1ao1*. This sequence has a match at level *h* = 1. *ao1* and *ao2* are potential successors. b) Prediction by rearranging eSMCs in new combinations. For continuing the prediction of the branch *ao1ao1ao2*, no match is found in the tree. The oldest events are successively discarded until a match is found again (*ao2*). The resulting sequences are *ao1ao1ao2ao1ao3* and *ao1ao1ao2ao3ao1*. [Source: Maye and Engel 2012b]

In a further elaboration of this model (Maye and Engel, 2012b), the data structure of past SMCs was stored in a tree structure (Figure 8). This enabled the system to predict multiple timesteps ahead. Note that, if the system has not previously seen all of the steps on the sensorimotor path that the robot has just taken (and/or for which it needs to make a prediction), it can make a match by discarding history steps until it has a short enough history to find a match. In this way, by a combination of 'memory' (the stored tree graph) and 'imagination' (the process of discarding history where necessary, in order to predict the future) the robot can in principle predict an arbitrary number of timesteps into the future. As in the previous example, an acting system also needs some form of evaluation function, and some way to balance 'exploration' against 'exploitation' of known (already experienced) SMCs sequences.

Using this extended probabilistic system, it was demonstrated that a real robot can not only learn Markov-style SMCs from the action-observation structure of its habitat, but could also plan ahead (solving an object avoidance task which could not be solved without making motor commands some time steps in advance of a collision). Furthermore, this controller structure allowed the robot to respond appropriately to novel objects in its environment (based on SMCs it had previously learnt). Finally, using only a relatively simple exploration/exploitation heuristic, this controller also successfully reverted to learning and mastering new SMCs, if novel objects were introduced which caused new SMC patterns which had not previously been observed.

3.2.1 Timescale-based SMCs

It should be noted that this approach makes it easy to compare SMCs at different timescales. This allows the following theoretical partition of SMCs (see also Section 5):

- Modality-related SMCs: immediate action-observation correlations (timescale length = 1); these mostly reflect properties of the sensory (and motor) interfaces.
- Object-related SMCs: short to medium length action-observation correlations (in the empirical work so far carried out, this corresponds to history lengths between 2 and approximately 10 timesteps); these SMCs reflect interactions with parts of the environment over a period of time.
- Intention-related SMCs: these are hypothesized to correspond to long-term action-observation correlations, within which the regularities necessary to engage in long-term planning may be detected.

As predicted by the first two steps in the above framework, it was demonstrated that robots considering only the shortest timescale SMCs could successfully respond to simple environmental features, but that features corresponding more closely to the notion of 'object' (e.g. features involving width and extent) could only be detected by using higher order (longer history) Markov models (Maye and Engel, 2011; 2012a).

3.2.2 Analysis of the Probabilistic Approach

One advantage of the probabilistic approach to SMCs is that it emphasizes the requirement that SMCs should be learnable, and indeed provides a mechanism for learning them. This mechanism has already been proven to be successful in certain real-world environmental tasks.

The claim that short-term SMCs correspond to sensory modalities, and that medium-term SMCs correspond to objects, is a useful clarification, but may arguably need refinement. For instance, the SO(3) symmetries of solid object rotations are (implicitly) present in single time-step action-observation pairs, for any interaction with a real solid 3D object (see related work by Philipona et al., 2003; 2004). A sufficiently complex model could capture and predict this single-timestep regularity (hence, a Bayesian update system incorporating such a mathematically complex model could in principle be used to confirm or disconfirm the presence of such single-timestep object-related regularities).

This relates to the more general point, that treating SMCs as probabilistic is a highly general framework for learning SMCs, and in principle a powerful framework, with applications beyond the short-history Markov models currently studied. To further develop this more general approach, we will need to consider the kind of Bayesian priors, which are required, in order to usefully learn complex (for instance, 3D object) SMC structures. This raises both pragmatic and philosophical issues about the required prior knowledge, in order to perceive the world, which we hope to address further.

As regards the notion that long and very long history lengths correspond to intention-related SMCs, we can see that this suggestion is theoretically motivated, but not yet proven. The same point applies to the similarly bold claim that the operational analysis of SMCs can be extended to include intrinsically normative frameworks. We return to these issues in the next section.

3.3 Comparison of the Operational and Markov Analyses of SMCs

It should be emphasized that the two theoretical approaches just reviewed – the dynamical and the probabilistic – have somewhat different aims within the eSMCs project, but that they are compatible with each other, and mutually co-informing.

The probabilistic framework introduces a practical method for learning environmental SMCs, which has already been shown to be successful in real tasks on physical robot platforms.

The dynamical analysis successfully relates the SMC framework as a whole to the large body of existing work in minimal embodied cognition (Beer, 1996; Slocum, Downey and Beer, 2002; Izquierdo-Torres and Di Paolo, 2005; etc.), and clarifies how these two different approaches to embodied cognition can inform each other.

3.3.1 Common Ground

It is important to emphasize that there are several important senses in which these two complementary approaches to SMCs speak a mutually compatible language.

The probabilistic account, when considered descriptive only of the relation between an agent's actions and sensory outcomes, could in fact be considered a stochastic extension of the dynamical systems approach. For example, if the minimal model operationally analysed above was not state-determined but rather a stochastic system (adding, say, sensory or motor noise), then the SM environment would no longer be captured by a simple surface. Instead of a single sensory reading (or sensory change) for each position and motor command, one would now have a whole range of possible sensor readings. If one represented this range as a probability distribution, then the SM environment would now have a thickness and density, given by the probability distribution at every point. SMCs in the probabilistic approach, represented by two-dimensional and discrete plots of sensory changes resulting from a given action (Maye and Engel, 2011), would then correspond to slices through this thick surface, sampled with a resolution that is given by the chosen discretization.

In addition, the idea of SMCs at different timescales can equally well be captured in the dynamical systems approach. Given an agent's SM habitat, i.e. a description of all its possible closed-loop dynamics, represented e.g., by an attractor landscape, one can map the sensory changes that result from allowing the dynamics to play out over different periods of time. The emerging structures of this map would mostly reflect properties of the sensorimotor interface if the period was very short (e.g., sensory stimulation moves to the left on the sensor when the agent moves to the right), properties of environmental features if the period was longer (sensory readings increasing as the agent approaches the peak), or the task as a whole (a successful agent will eventually have either small oscillating sensory activation when at the centre of the desired shape, or zero activity after moving away from those to be avoided).

3.3.2 Philosophical Differences, and Approaches to Potential Resolutions

In common with many authors writing within the enactive tradition (Brooks, 1991; Harvey et al., 1996; etc.), the present review document has discussed above (Section 2.2) the dangers of taking an overly internalist or representationalist approach to cognition. In contrast, and in common with much (although not all) work in robotic cognition, the Markov-probabilistic implementation of SMCs described above could be understood as quite representationalist. In particular, the specific action-observation probabilities that the robot encounters are *explicitly* stored internally and manipulated by the control-system of the robot. On the other hand, it is true that the system is not 'representation hungry' (Clark and Toribio, 1994) in that 'knowledge' about 'objects' is *not* explicitly stored, but rather emerges, as a whole-system property, when the a robot controlled by the specific probabilistic implementation is allowed to interact with the world. As such, the most obvious reading of the probabilistic approach (as developed so far), is that agent-level knowledge, such as knowledge of 'what an object is', emerges as a whole-system property, in interaction with the world; but nevertheless, it is still the job of the brain (or equivalent controller) to explicitly evaluate, store and process SMC probabilities.

In contrast, the operational-dynamical account has aimed to clarify what the fundamental term SMC, and related linkage terms, could mean, without assuming any particular computational implementation or metaphor. It shows that, at least in the simple cases considered so far, explicit representation and storage of information about the consequences of an agent's actions are not always necessary for the concept of SMC to be a useful explanatory tool. It has also suggested the possibility that regularities resulting from all aspects of the agent's embodiment can help create useful features in the agent-environment dynamics; and it has suggested that, in principle, these dynamics could become attuned to an intrinsic normative dimension (for instance, the need for self preservation), again without any explicit, internal information storage.

There seem to be two obvious possibilities for resolving the apparent tension between these two analyses, on this issue. One would be to show that the probabilistic approach to SMCs actually (if implicitly) defines certain key aspects of what a robot should *do*, in order to learn and master SMCs; and that these requirements can be expressed at a level which does *not* require or specify any particular implementation. In that case, maybe the lower level dynamical attunement suggested by the operational-dynamical approach might be one natural way to achieve ‘probabilistic learning of SMCs’ (now considered as something that agents, and not internal systems, need to do, to successfully inhabit their worlds).

Another, rather different, resolution would be to attempt to show that, to the extent that a dynamical system does indeed learn and master SMCs, so also we can logically expect to be able to find ways of interpreting its internal variables as storing and processing action-observation probabilities.

We have to admit that we don’t find the second option attractive, and that the first option remains, for now, speculative at best. However, having established that there are indeed several pragmatic overlaps between the two approaches, we plan to do more to resolve (or at least further clarify and explore) the apparent conceptual differences between the two.

As a final area of further work, we note that both the dynamical-operational framework and the probabilistic framework have indicated that they hope to be able to discuss, in future work, how to incorporate ‘norms’ (i.e. level 4 of the operational framework) or ‘intentions’ (i.e. level 3 of the probabilistic framework) (see also Section 5). With regard to the minimal cognition literature, to which the operational approach links, there is considerable hope that normative notions can be grounded in operationalized concepts such as autopoiesis (Varela et al., 1991), or else in the related (but more general) concept of adaptivity (Di Paolo, 2005). The original SMC approach (O’Regan and Noë, 2001), on the other hand, is arguably closely allied to an extensive tradition in analytic philosophy that suggests that norms cannot be operationalized (“you can’t get an ‘ought’ from an ‘is’”) (Moore, 1903; Davidson, 1973; McDowell, 1994).

Once again, there is a fundamental philosophical tension here (which is relevant to, but certainly not unique to, this project), which we intend to further explore and analyse in the mutual co-informing further development of the approaches to SMCs outlined above.

3.4 Dynamical SMCs and information theoretic measures

Yet another methodology for describing sensorimotor relationships, that of information theoretic measures, has been adopted within the eSMCs project, and it too can be related to the kinds of operationalization offered in section 3. In (Schmidt et al., 2012), the authors have studied the statistical information transfer relationships between the different sensors and motors of a compliant quadruped robot that is controlled by either random or coordinated (but open-loop) leg actuations (the Robot Puppy). Instead of analysing the particular sensory consequences of given actions, however, the approach here extracts more abstract information about the SM coupling, namely the directional correlations between the various sensors and motors. The random controller, which does not exhibit the same kind of correlations in motor signals as the coordinated controllers, is shown to reflect mostly the effects of the environment (contact with the floor surface) and the body structure (hip actuators driving hip angle sensors in the same leg), see Figure 9. The information extracted from this open-loop test corresponds to the concept of SM environment in the dynamical account, where motor commands are eliminated from the sensorimotor loop. It provides a description of the constraints of the agent's embodiment in a given environmental context (or what the authors call a body schema).

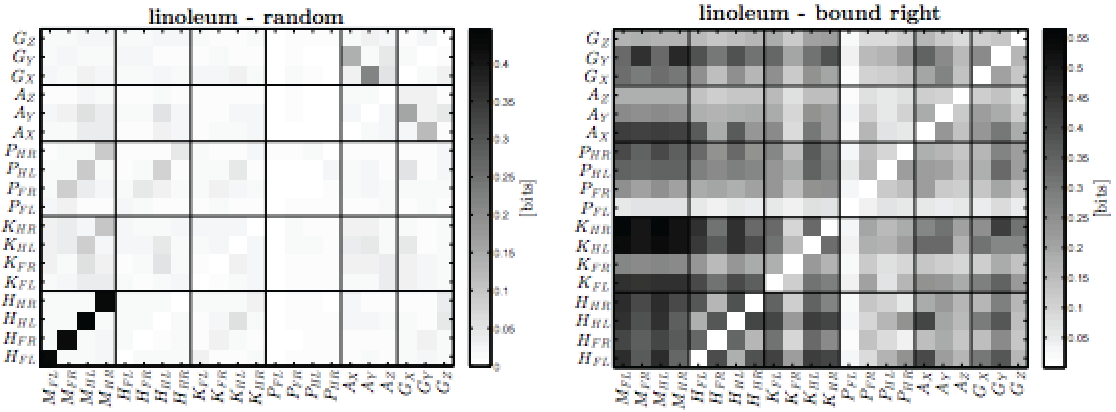

Figure 9: Transfer entropy for two types of controllers. Cells of the matrix correspond to the information transferred from signals in the columns to signals in the rows. Left: for the random controller little information is being transferred overall. Most salient is the dependency between hip angle sensors and corresponding motors. Right: the regularity induced by the bound-right controller, i.e. the "behaving" agent, leads to a more complex pattern of information transfer, now also between different legs. Figure adapted from (Schmidt et al. 2012).

Introducing coordinated movement patterns, further informational dependencies are induced through the regular time-extended behaviour of the agent's gait. For example, information transfer now also occurs among variables belonging to different legs, and certain dependencies reflect properties of the task, such as more information being transferred between some variables when turning rather than walking straight. Here, though the system is still open-loop with respect to motor commands, the analysis takes into account the ongoing interaction between agent and environment during a "meaningful" task, not unlike the notions of SM habitat and SM coordination provided in the dynamical account.

We can see that the four definitions of SMCs introduce distinctions, which though derived from a dynamical perspective, are general enough to apply to other methodologies as well. Conversely, the information-theoretic approach demonstrates that useful information about the various dynamical SM structures can be obtained even without analysing (or indeed being in possession of) a complete set of dynamical equations describing the agent and the environment.

4 The role of sensorimotor knowledge in motor control

Sensorimotor contingencies are law-like relations between an agent's actions and their sensory consequences. It is however the acquisition and exercise of *knowledge* of these laws that constitutes perception according to the original formulation of SMCT. Ignoring for now the controversy about the importance of the notion of "knowledge of SMCs" in the theory (Hutto, 2005; Clarke, 2006; Roberts, 2009), the idea would seem to have close connections with the concept of internal model in the computational motor control literature. The latter expresses the belief that the brain can simulate the consequences of a motor command to predict the resulting changes in sensory feedback. The original formulation of SMCT does not explicitly mention the ability to predict sensory consequences, but this is often implied. For example, it is argued that sometimes complete sensory information is not needed to perceive a given object, because one's brain is attuned to "certain potentialities", i.e. the knowledge that if we *were* to move in a certain way, the sensory feedback *would* change in such and such a way (e.g. see O'Regan and Noë, 2001, p. 945). Connections have also been made between SMCs and the concept of body schema, predictive coding and the free-energy principle, all of which can be considered theories related to the idea of internal models and simulations. Because of this connection between SMCT and the concept of internal model, it is worth critically examining the use of, and evidence for such models in computational motor control, where the idea originated. If it could be shown that the brain does not need to simulate the consequences of actions internally, or even that this is impossible, then this would also cast doubt on the adoption of the concept (without re-interpretation of its meaning) within SMCT. Without a clear delineation of the idea of knowledge of SMCs from similar notions like internal model, body representation, simulation and prediction, the danger is that one replaces the idea of a detailed internal model of the world with that of a detailed internal model of the body. Clarifying these concepts is also necessary for creating the foundation of an SMC approach to action proper. Much in line with the original contribution of SMCT in perception (that perception is not about storing internal model of environmental objects), SMCT can contribute to a theory of action where action is not just the motor expression of an internal control model, but the mastery of "motor-sensory" contingencies that are available to the body.

4.1 Internal models and physiological reality

According to computational theories of motor control the problem of movement generation essentially concerns how a desired movement, defined in spatial coordinates, is transformed into the necessary forces to be applied by the muscles. To compute this transformation, the system uses internal representations of the geometry as well as the dynamical equations of motion of the body. The former is used to calculate inverse kinematics, e.g. the joint angles required to position the hand at a particular point in space. The latter is used in an inverse dynamics process to calculate the joint torques or muscle forces necessary to achieve the desired joint angles. In addition, computational approaches often employ forward models, which use a copy of the motor command (efference copy) to predict the sensory consequences of a movement. It has been argued that forward models are necessary, for example, to adjust control signals on the basis of anticipated sensory consequences in order to mitigate the detrimental effect of delays and noise in actual feedback (Smith predictor, Kalman filter); to distinguish between sensory consequences of self-initiated actions (reafference) and sensory stimulation resulting from externally imposed movement (ex-afference); to explain the apparent stability of the world throughout movements of the head or eyes; and to account for anticipatory postural adjustments in accordance with expected disturbances (anticipatory grip-force modulation). In general, there is a growing trend arguing that organisms need to be able to predict the sensory consequences of their own actions to be capable of fast and adaptive behaviour, and that internal modelling provides a unifying framework for understanding cognition in general (Grush, 2004; Wolpert, 2003). In the following we examine evidence for three assumptions underlying this approach: the brain centrally specifies forces to be applied by the muscles; these forces are derived using an inverse dynamics model; the motor system uses predictive mechanisms based on forward models.

Regarding the assumption of direct force control by the brain, current evidence suggests it is rather unlikely that a single control variable can account for all types of movements occurring naturally. For example, even though correlations can be found between neural activity and joint torques, muscle activity or direction of required force output (Gottlieb et al., 1990; Georgopoulos et al., 1992), this is also true for hand direction, velocity, movement distance or arm geometry (Georgopoulos et al., 1982; Schwartz, 1993; Fu et al., 1995; Scott et al., 1997). In fact, neurons in motor cortex seem to be tuned to complex patterns, including many muscles and joints, that reflect the behavioural repertoire of the animal, such as hand to mouth movements, or reaching out and grasping (Graziano, 2006). The direct force control approach is also limited by its inability to resolve the posture-movement problem as first identified by Holst and Mittelstaedt (1950), i.e. the fact that even though the body is reflexively stabilized in any particular pose, we can also move between poses without triggering resistance. Computational motor control usually neglects such peripheral dynamics, or has to falsely assume that postural reflexes are suppressed (Won and Hogan, 1995).

Support for inverse models comes from experiments with deafferented monkeys that can perform basic reaching movements in the absence of proprioceptive feedback (Polit and Bizzi, 1979). However, the observed movements were so limited and crude, and the required training so extensive, that the original authors concluded that the "dramatic inability of the deafferented monkey to execute accurate pointing responses [...] underscores the great importance of afferent feedback in updating and adjusting the execution of learned motor patterns". Purported evidence also comes from the observation that subjects executing reaching movements in an external force field show adaptation and after-effects (Shadmehr and Mussa-Ivaldi, 1994). The proposal is that internal models learn to adjust for the external forces, but once the latter are removed, misrepresent physical reality. Such experiments, however, merely show that humans (and monkeys) can take loads into account when performing arm movements. Gribble and Ostry (2000) have demonstrated that this is possible also without representation of forces, inverse dynamics or forward predictive simulation. Finally, some argue that a complete inverse model is, if not theoretically impossible, physiologically implausible given the huge redundancy between external coordinates and the approx. 200.000 motor neurons, and the complex non-linearities on the level of neural, skeletal and muscle dynamics (Zajac, 2002).

Evidence in favour of forward models is even more difficult to establish, as they affect motor output only indirectly. Also, every output-predicting controller can in theory be replaced with a direct control scheme that does not use internal models but has exactly the same input-output function (Mehta and Schaal, 2002). In this light, behavioural studies and those demonstrating differential neural activity in situations like self- vs. externally generated tickling (Blakemore et al., 1998), anticipatory grip-force modulation (Kawato et al., 2003), mirror neuron activity during action observation, or the estimation of arm position after movement in the dark (Wolpert et al., 1995) cannot offer direct evidence for forward models. At best they offer one possible hypothesis about anticipatory forms of behaviour, which often can be achieved also without internal models (Ostry and Feldman, 2003; Barto et al., 1999). Finally, noisy and delayed feedback might not be as detrimental as is usually claimed, and natural movement can often be achieved in their presence without internal models (Brown and Loeb, 2000; Ali et al., 1998, St-Onge et al., 1997; Pilon and Feldman, 2006).

There is no doubt that human motor control features predictive or anticipatory mechanisms that can detect and compensate for the effects of self-induced motion or novel sensorimotor environments. It is a valid question, though, whether these are implemented in the nervous system as detailed and accurate predictive simulations of the body and/or the external world. Simple animals have capacities like those often explained with the aid of internal models. Webb (2004) notes, for example, that flies can distinguish self-generated visual slip from external disturbances for flight stabilization. But it is unlikely that their small brains contain a model that can simulate the effect of muscle activity on wing movements, the resulting change in body orientation, the change in visual input in response to body movement and finally the response of visual receptors to the resulting change in the visual flow field. A range of other anticipatory animal behaviours have been demonstrated to make use of efference copy, which range in complexity from simple gating of a sensory channel to the precise matching of timing and duration of sensory inhibition to the predicted sensory consequence. It is arguable whether one can label any of these mechanisms as involving internal models or simulations without making the notion too thin. And in general, it is an empirical question where on the sliding scale between simple efference copy and accurate, complete forward model a particular anticipatory mechanism resides.

4.2 Alternative to internal models

An alternative to computational motor control is proposed in the equilibrium-point (EP) hypothesis (Feldman and Levin, 2009). This hypothesis originates in the physiological finding that muscles and reflexes together act like non-linear springs whose set-point can be modulated by descending signals from the CNS (Matthews 1959, Feldman 1966). The suggestion is that central motor commands act on the tonic stretch reflex by changing a component of the threshold length beyond which a muscle becomes activated (Feldman, 1966). If the muscle is stretched beyond this threshold, it will be activated it in proportion to the difference between actual and threshold length as sensed by proprioceptors, which in turn will produce contraction, thus bringing its length closer to the threshold value. The continuous interaction of neural and muscular elements will thus drive the system towards a new position and state of minimal muscle activation. The mechanism thus resolves the posture-movement problem (mentioned above), explains why intermediate postures are stabilized against perturbations, and the observation that muscle activity (EMG) is generally absent before and after a movement. Threshold control is distinguished from force control by the fact that it implies a positional coordinate frame of motor control (muscle lengths), and in that it does not require any inverse dynamics calculation of muscle forces.

Threshold control schemes have successfully been employed in addressing problems of redundancy (Balasubramaniam and Feldman, 2004), vertical posture stability (Micheau et al., 2003), human walking (Guenther and Ruder, 2003), sense of effort (Feldman and Latash, 1982), and in relating kinematics, dynamics and EMG patterns in point to point reaching movements (Feldman et al., 1990; Latash, 1993; Gribble et al., 1998). Despite various claims to the contrary (mostly based on models that oversimplified the natural dynamics of the musculoskeletal system), this type of control has also been shown to be consistent with empirically observed levels of damping and stiffness (Gribble 1998, Kistemaker, 2006) and feedback delays (St-Onge et al., 1997, Pilon and Feldman, 2006). It has also been employed in models of behaviours usually thought to require internal models, such as load adaptation (Gribble and Ostry, 2000) and anticipatory grip-force modulation (Pilon et al., 2007).

In the eSMCs project we have recently added to this list by addressing the question of whether internal models are required to predict and explicitly counteract the passive inter-segmental dynamics that occur during movements involving multiple limb segments (Buhrmann and Di Paolo, forthcoming). Evidence suggests that humans do in fact take interaction torques into account when planning or controlling their movements. Using a model of the human upper arm that includes two pairs of simulated muscles and the spinal circuitry innervating them (see Figure 10), we show that proprioceptive feedback alone, coupling spinal circuits that regulate different joints, can implicitly account for the effect of such forces; without the need for internal models.

From a broader perspective, threshold control implies a view that it shares with SMCT, namely the idea of a tight linkage, or parity, between perception and action. The requirement for internal models in motor control partly stems from the assumption that motor commands and sensory consequences are expressed in different coordinates, forward models being responsible for their translation. Threshold control, in contrast, implies that motor control on the lowest level is expressed in the same coordinates as the feedback, namely changes in stretch-reflex threshold coordinates (muscle length). An extension of threshold control proposes that the same holds true on higher levels of the motor control hierarchy (Feldman, 2011). If motor commands were (always) expressed in the same coordinates as sensory consequences, then a forward model would not be needed to translate efference copy into sensory coordinates. Movement generation could then be seen equally as motor- or sensory control. What is specified in goal-directed action is the desired sensory consequence of the goal rather than the muscle forces, that is, both actions and perceptions are encoded in the same sensorimotor frame of reference (Feldman, 2008, 2009). This bears some resemblances with Perceptual Control Theory (Powers, 1973) and Common Coding Theory (Prinz, 1997).

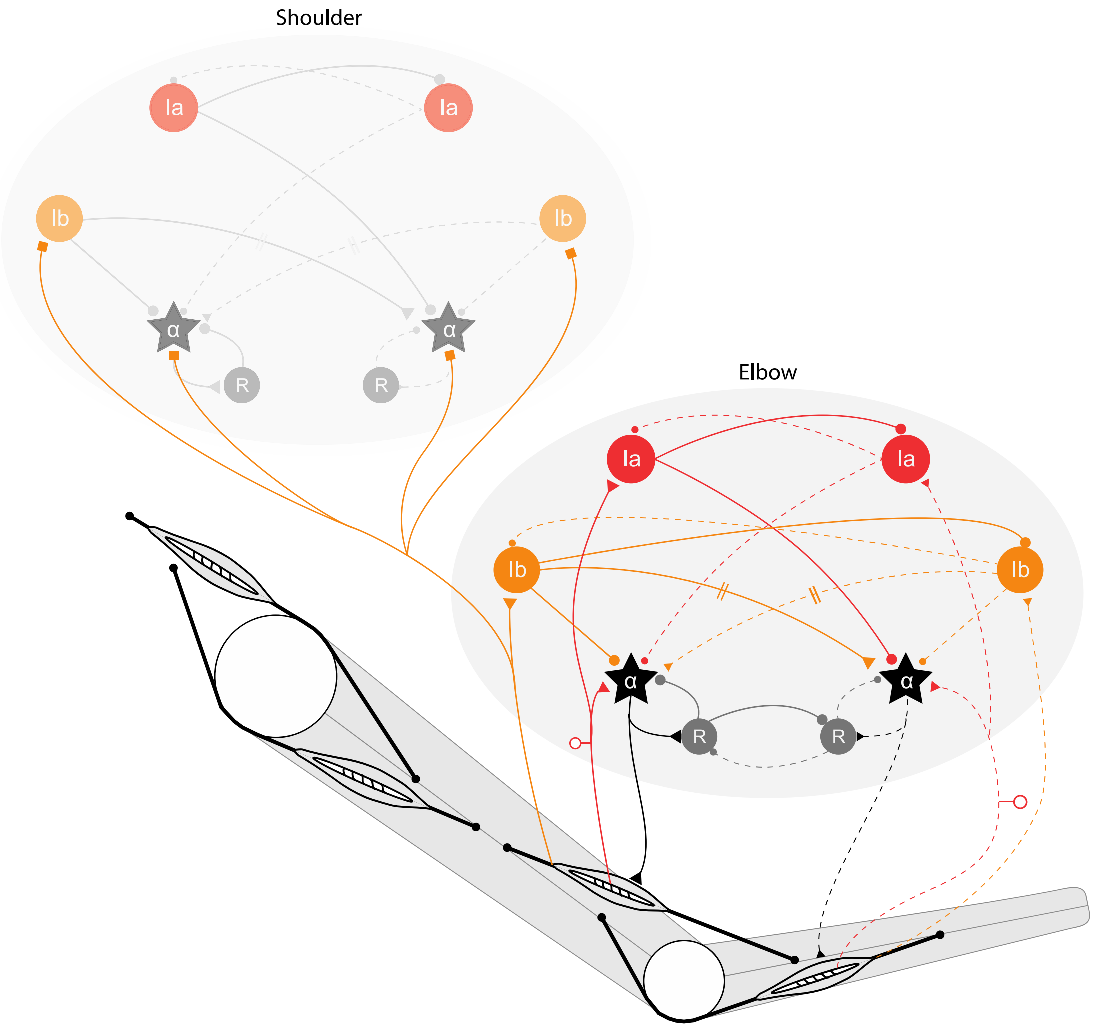

Figure 10: Model of two-degree of freedom arm controlled by two antagonistic muscle pairs shown with their local spinal circuitry. Ia pathways are shown in red, Ib pathways in orange, and Renshaw cells in gray. Agonist related circuitry is drawn with solid lines and antagonists dashed. For clarity the shoulder circuitry is shown in less detail. Distribution of Ib afferents across joints is hypothesized to be responsible for their coordination, implicitly accounting for internal loads.

4.3 Conclusion

To summarize, most researchers in the field of motor control now support the view that the brain requires detailed internal models of the body in order to deal with the complex dynamics of the musculoskeletal system, with noisy and delayed feedback, or to distinguish between self-generated and externally imposed movements. Critics point to a paucity of concrete evidence to support this view, doubt the general feasibility of (learning) such models, propose alternative theories, and claim that other, often simpler, anticipatory mechanisms are often sufficient. Yet, many recent theories in cognitive science have adopted the internal model view in order to explain higher-level cognitive capabilities. Grush (2004), for example, proposes that internal models of the body and the environment, whose primary purpose is to improve motor control and perception, can be run offline to produce visual imagery, reasoning, and language. Similar extensions have been proposed for social interaction, imitation and mindreading (Wolpert et al. 2003; Hurley, 2008). It might seem a logical step to also build SMCT on the idea of internal models as concrete implementations of concepts such as "knowledge of SMCs". The discussion above, however, indicates that notions such as internal models predicting, simulating or emulating the body's actions should be used with extreme care, since even a quick examination often reveals either an unwarranted applicability or a trivialization of their use. Not all functional efferent copies result in predictions, not all sensorily, bodily and environmentally attuned motor commands result from emulations.

5 The constitutive role of sensorimotor coupling in SMCT

There is a further philosophical debate which some see as threatening to undermine the significance of SMCT and its possible foundational role for cognitive science. The central objection to SCMT is that, despite a possible involvement of action in perception, there are empirical and conceptual reasons to claim that action (or motor variation) is, at most, *causally* relevant for perception but not in any sense *constitutive* of perception (or, by extension, of other cognitive processes). In other words, action might play a role in perception, but this role is not *essential*. If this is correct, SMCT would leave the core of traditional representational approaches unaffected, it would only add some level of detail about how some processes that lead to perception or cognition are sometimes accompanied by action, but would never become a radical challenge. To put it in other terms: it is not that "perception *is* a form of action" as SMCT claims, but simply that "perception *can* sometimes result from, or be caused by, actions".

Empirical and conceptual arguments have been developed to dismiss the constitutive role of action for perception. We shall first address some of the most relevant empirical criticism and then move into the more conceptual challenges.

5.1 Neuroscientific evidence on the link between perception and action

We shall focus on Prinz's empirical arguments against Nöe's enactive SMCT because it provides a battery of neuro-scientifically grounded arguments; some of which have been recurrent along different attacks to SMCT, like the dual stream theory of vision—also invoked by Clark (2006) and Block (2005)—and because they are all representative of the mainstream positions in cognitive neuroscience regarding perceptual awareness.

The central claim against SMCT is that "[N]euroscience provides an overwhelming case for the view that perception is not essentially linked to action" (Prinz, 2006, p.11). Against this claim we shall summarize some neuroscientific evidence showing that perception *is* "essentially" (more on this term latter) linked to sensorimotor dynamics at developmental, anatomical, and functional scales.

One of the most cited pieces of supporting evidence for enactive development comes from Held and Hein's experiments (1963). Two kittens were reared by holding one immobile and attached to the other, so that both received the same sensory stimulation, yet only one had the freedom to control its own movements. After a period of development, the kittens were tested in different perceptual tasks, whose behavioural consequences allowed assessment of whether each kitten was capable of correct visual discrimination. In one of these experiments, the originally immobile kitten was placed in front of a visual cliff (covered with transparent glass), which it walked across without noticing. Prinz dismisses Held and Hein's experiments by interpreting that the immobile kitten just "did not have enough experience walking on edges". But, neither did the freely moving kitten, yet it showed no incapacity to perceive the cliff and avoid it. However, we will concede to Prinz that some of these experiments might not be able to disambiguate with sufficient accuracy between perceptual dysfunction and perception-action coordination problems. Unfortunately for Prinz, and his categorical assertion that "the Held and Hein study was never replicated", later studies have indeed supported the perceptual dysfunction interpretation with further evidence from studies lesioning the ocular muscles of kittens and identifying selective neuronal blindness for visual features orthogonal to the movements made by the lesioned muscles (Buisseret, Gary-Bobo and Milleret, 1988).

Prinz wants to strengthen his claim against the developmental role of action for perception by claiming that "studies of human infants with muscle atrophy show that when humans are prevented from moving in early development, there is no decrement in the visual comprehension of space" (Prinz, 2006, p. 10). And yet, examples of spinal muscular atrophy do not invalidate sensorimotor accounts of perceptual development, since head and saccadic eye movements are perfectly intact in those cases. The enactivist claim is not that all forms of motor function need to be intact in order to develop "normal" perception. What is required is that the developing organisms have access to the way in which perspectival changes and movements affects sensory stimulation. However, developmental facts are not decisive. No matter how development occurs, current perceptual experience might not necessarily depend on motor activity. Simply put, physiological conditions for correct development are often different from the conditions necessary to correctly carry out physiological functions.

Perhaps the strongest of Prinz's claims regarding the actual lack of evidence for action in perception is the following:

> "If the brain areas that are known (because of their behavioural consequences) to encode the motor consequences of visual stimuli are not implicated in visual consciousness, then there is no reason to think Noë's theory of consciousness is correct. Noë is forced to say that representations in the ventral visual stream are also involved in the coordination of action, but there is absolutely no evidence for this conjecture. All evidence implicates the dorsal stream." (Prinz, 2006, p.10)

Prinz is here referring to the "two stream theory of vision" (Goodale & Milner, 1992), which states that there are two distinct visual pathways: the dorsal stream (also referred as "vision for action") and and the ventral stream (or "vision for perception"). First, it is important to note Noë's insistence on the fact that "the enactive approach is not committed to the idea that vision is for the guidance of action, so neither the fact that some visual processing is for the guidance of action, nor the fact that some visual processing is not, has any direct bearing on the enactive approach" (Noë, 2004, p.19). Nevertheless, there is evidence for action in perception along the ventral stream ("vision for perception"). In a recent review of the two stream theory (Milner & Goodale, 2008) the authors of the theory remind us that "there is complementary evidence that supports a ventral-stream role in the planning of action" (p.776) and that "in most normal circumstances, our actions will be visually co-determined by complementary processing in both dorsal and ventral streams" (p.776). More importantly, they also take it as experimentally confirmed that the ventral stream is used to coordinate sensorimotor tasks when the movements are awkward or not automatized. Visual illusions, for example, that only affect the ventral stream, still have consequences for reaching and grasping when subjects are asked to do so with the left hand or in non-automatized situations (Gonzalez et al., 2008). Milner and Goodale conclude that "only highly practiced actions with the right hand operating in real time and directed at visible targets presented in the context of high-level illusions are likely to escape the intrusion of ventral-stream perceptual control" (Milner & Goodale, 2008, p. 780). Thus it turns out that the vision-for-perception stream is actually involved in precisely those aspects of movement planning and execution that require conscious control. These empirical facts refute Prinz's bold claim that there is "absolutely no evidence" for ventral stream involvement in the coordination of action.

Part of Prinz's refusal to include a role for action in perception is that he conceives of a rather one-directional sequence of causation in the form: world → eye → V1 → … → V4. The main idea of his theory is that consciousness arises when intermediate-level representations (activity e.g., in visual cortex areas V3, V4) are modulated by attention, ignoring any possible role for motor and pre-motor activity (Prinz, 2000). His serial account of visual processing ignores, however, the many recurrent and parallel pathways mediating modulation of visual information even in early stages of processing. He chooses, for instance, to ignore modulations at the level of the thalamus (and in particular the lateral geniculate nucleus, LGN), which though primarily thought to relay visual information from the retina to V1, receives only 10% of its connections from the retina and the rest from other parts of the brain. Neurological evidence now exists that suggests such modulatory inputs involve attentional and premotor processes in early visual perception (Briggs and Usrey, 2011; Kastner et al., 2006; Royal et al., 2005). For example, it has been demonstrated that effects of saccadic eye movements alter "not only response strength but also the temporal and chromatic properties of the receptive field" of neurons in LGN (Reppas et al., 2002, p. 961). Also, efference copies related to higher-level motor planning have been shown to influence LGN activity (Royal et al., 2005). We can therefore conclude that it is untenable to claim that "V1 is a primary source of inputs to another region in which consciousness can rightfully be said to reside" (Prinz, 2000, p. 246) without considering LGN as a proxy for motor influences on V1, and consequently on visual awareness.

Once it is shown that neuroscientific evidence is insufficient to rule out an essential role of action in perception, it still remains necessary to show that action, and more generally the SM habitat and SM coordinations, are constitutive parts of the processes that lead to perceptual awareness. The problem is how to assemble data into an operational hypotheses about sensorimotor constitution.

5.2 A proof of concept for the constitutive role of sensorimotor coupling

The conceptual discussion concerning the causal or constitutive role of action for perception involves the ontological and explanatory status of SMCs. Broadly speaking we can summarize the debate along two major and opposing positions:

> **Internalism + causal role of action for perception:**
> Perception supervenes on brain states/processes. Actions can alter environmental or sensory states, which in turn cause appropriate neural correlates of perceptual awareness, but other causes of the "right" sensory input would be equally valid to produce the brain state that is ultimately responsible for perceptual awareness.
>
> **Externalism + constitutive role of action for perception:**
> Perception supervenes on brain-body-environment states/processes. The environment (or the SMCs it supports) is part of the processes that define a particular perceptual state.

Critiques coming from internalist-causal positions have challenged externalist-constitutive accounts demanding that it be shown how changes in the environment (while keeping the brain fixed) could alter perceptual states. This challenge has not been met and it is perhaps reasonable to assume that it will never be. And yet, authors defending SMC theory have not provided a response to this criticism. But SMCT need not go as far as showing that a change in the environment will produce a change in perception (without brain changes taking place) in order to claim a constitutive role for SMCs in perception. In order to illustrate this possibility (in a manner that could be used to design empirical experiments) we can rely on experiments carried out as part of the eSMCs project, based on the *situated HKB model* developed by Aguilera et al. (2013) and Santos et al. (2013). The goal of this model is to illustrate an operational hypotheses about sensorimotor constitution, and use it as a proof of concept of how the SM habitat and patterns of SM coordinations (as defined in section 3) can become essential parts of a minimal cognitive or adaptive processes: that is, to provide a minimal neuro-behavioural scenario where causation could be distinguished from constitution.

The situated HKB model implements the extended Haken-Kelso-Bunz model (Kelso 1995)—which captures the behaviour of a collective variable φ representing the phase difference between two coupled oscillators—and employs it as a behavioural controller for a robot. Its dynamics are described fully by the following equation:

$$\varphi' = (\Delta w_0 + I) - a \sin(\varphi) - 2b \sin(2\varphi)$$

where φ is the relative phase between two interacting oscillators; a and b are the coupling coefficients; and $\Delta\omega$ is the difference between the intrinsic frequencies of the pair of oscillators. The agent is sensitive to the gradient of an intensity signal η present in the environment:

$$I = \eta'(p)*s$$

where the perceived intensity signal *I* depends on the position of the agent *p*, and *s* is a sensitivity parameter that is fixed during the task. In turn, the agent's motors are modulated by the variable φ:

$$Mr(\varphi) = m*\cos(\varphi)$$
$$Ml(\varphi) = m*\cos(\varphi+c)$$

Together, these equations describe the closed-loop behaviour of a situated agent that conforms to the same dynamical framework introduced in section 3. When the agent moves in the environment its sensor receives new inputs (variation of I). The varying sensory signal influences the frequency difference between the two oscillators (variation of w) and indirectly leads to a change in their relative phase difference (variation of φ). Finally, variations in phase difference induce a change in the balance of the motor outputs (variation of $M(\varphi)$), which results in a change of the robot's position, thereby closing the loop.

We optimized the agent's parameters (s, a, b, Δw_0, c) to perform a gradient climbing task: a source of gradient is situated in the environment and the robot can reach the peak of the gradient starting from different initial positions and orientations.

We assess the importance of sensorimotor-coupling by comparing the robot's "brain" dynamics under situated and passively-coupled conditions. We can understand these two conditions in analogy with the kittens in Held and Hein's experiment (1963): the situated robot behaves freely, receiving sensory input as a result of its own movements according to the stated equations. The passively-coupled agent, in contrast, receives sensory signals previously recorded from a situated agent. For this second agent, sensory variations are no longer the result of its own movements. We also compare these two conditions with the dynamics of an isolated HKB system that receives constant input or none at all (see Figure 11).

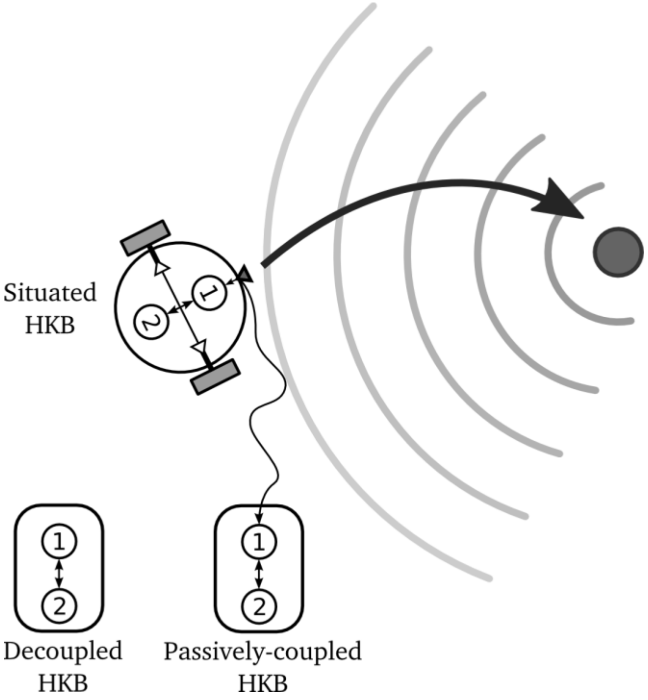

Figure 11: The HKB model for coordination dynamics under three different conditions: situated, where the agent receives a sensory input that changes with its motor activity as this produces displacements in the environment; passively-coupled, where the robot receives the exact same sensory stimulation as that of a freely behaving robot (but not caused by its own actions); and decoupled, with no or constant input.

Comparative results showed that the following phenomena could not be deduced from the analysis of the isolated or passively coupled systems, even when they receive the same sensory input:

1. the brain-body-environment system's phase transitions that occur for different values of the sensitivity parameter s
2. the attraction patterns of the controller's state space
3. the neurodynamic signatures of a gradient climbing agent's controllers (see below)
4. the robustness to fluctuations that the situated system displays

The comparison shows that fine-grained SM contingencies or coordinations are *essential* to create and sustain a particular neuro-cognitive process. In order to better illustrate the causation vs. constitution debate with this model we can focus on the last two qualitative differences between situated and passively coupled systems in terms of neurodynamic signatures.

The dynamic signature is meant to capture the neurodynamic correlate of gradient-climbing behaviour: i.e. a picture of the patterns of neural change that produce gradient climbing. Note that the neural correlate is not a single state (a specific value of φ), this is congruent with the fact that functionally identifiable neural correlates of awareness are not infinitesimal states but neural patterns that last around 100ms (Varela 1995). We define the signature as the density distribution over the effective phase space of the neural coordination variable. Figure 12 shows a comparison between the neurodynamic signature of a situated and a corresponding passively decoupled system. It is apparent that the signatures differ significantly, despite the fact that the passively coupled system is receiving the exact same sensory stimulation.

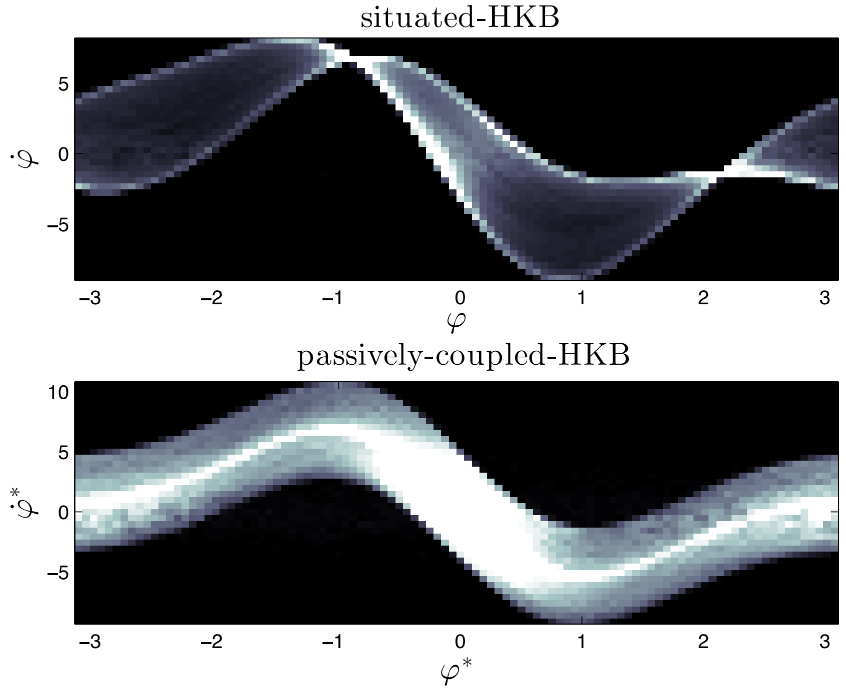

Figure 12: Signature of the situated HKB model with sensitivity parameter s = 2.5 and the corresponding passively-coupled model. It is represented here as the density distribution

over the effective phase space of the HKB equation when coupled with an environment [from Aguilera et al. submitted].

The results illustrate that even if we were to assume an internalist position about experience or cognition (mental state X supervenes on brain state Y, no matter what the state of the environment is), the neural signature that corresponds to a given behaviourally functional episode (like gradient climbing) in the situated agent is qualitatively different from that obtained in the passively-coupled system when the same input is induced and both systems are repeatedly simulated with small random variations in the initial state of φ (and position for the situated agent). Fine-grained sensorimotor coordination here is *necessary* to achieve functionally distinct neural signatures.

The situated HKB is a case of double coordination: sensorimotor coordination of the coordinated dynamics of the two oscillatory components (modelled by the HKB equation). What is crucial is the fact that under situated conditions the dynamics of the HKB can be modulated by the precise and interactively structured coordination between its internal dynamics and the sensorimotor environment. The mode in which sensory input (the control parameter) changes as function of the motor output (that is in turn generated by internal dynamics) through the environment makes possible this higher order coordination. It can be said that the agent modulates its internal dynamics through sensorimotor coordination, in a manner that is not available to the decoupled or passively coupled system, resulting in functionally specific internal patterns that we have captured with the dynamic signature.

If we conceive the SM-environment not as an external reality that we can access as experimenters or designers, but in terms of the changes in the sensory surface as a function of the motor variation (for a particular structure of the environment), we can more precisely depict the constitutive role of SMCs for perception: it is only "inside" this environment that certain neurodynamic signatures can come about and be sustained. It is in this sense that the environment can be constitutive of a given higher-level process (e.g. conscious awareness) and not a simple instrumental cause. It is only through the fine grained coordination between neural and sensorimotor activity that certain neurodynamic patterns can exist, and this coordination is only possible if the agent is directly coupled to the environment, not just passively or instrumentally coupled with it.

Now, this model is no proof that natural action is constitutive of perception, but it makes explicit how that could be the case, and what kind of experiment could give rise to empirical support. Recent experimental platforms in Substitutional Reality (SR) (Suzuki et al. 2012), together with neuroimaging techniques, can be used to replicate an experiment like the one performed with robots. In substitutional reality a subject is endowed with virtual reality glasses and either the live stream of a 360-degree camera or a previous recording is played to her as she moves her head. Some preliminary explorations have shown that "a major factor influencing successful substitution in the SR system was consistent visuo-motor coupling throughout the experience" (Suzuki et al., 2012, p.6). Although perceptual differences are noticed in the "sense of reality" (but not its experiential content) saccadic movements still take place "behind" the SR glasses. The crucial experiment would require a saccadic substitutional reality platform and the retinal stimulation of what a subject had previously generated with her saccadic movements but in a decoupled conditions; i.e. where the current sensory stimulation does not correlate with saccadic movement being produced.

6 Outlook

The previous sections lay the groundwork for a theoretically loaded approach to SMCT. The main ideas, as proposed by O'Regan and Noë, have been placed within the constellation of related approaches to embodied cognition (section 2), and the need for elaborating a dynamical approach to defining its central concepts has been defended in section 3, together with the presentation of positive proposals for defining SMCs in terms of different dynamical SM structures. This step (until now missing) is crucial for the application of SMCT to empirical and modelling research as well as for refining the theoretical debates that surround the whole approach. Some of these consequences have been shown in actual models and discussion of theoretical implications (sections 3 and 4).

We believe that these contributions help improve the framework of SMCT and make it more relevant for empirical and modelling research. However, this by no means exhausts the range of important questions related to this approach that still demand further development. This final section briefly points to this outlook of remaining issues. It partly summarises some of the discussion presented in Deliverable D1.1 but now from the added perspective of the novel contributions described in the previous sections. As many of these contributions are still under development, some passages remain speculative for the moment.

6.1 SM structures and agency, temporality, and plasticity

The four sensorimotor structures proposed as dynamical definitions of SMCs can help organize the study of different open questions. Here we briefly sketch the relevance of these concepts for the questions of agency, temporality and plasticity, which connect to some of the ongoing and future tasks of the eSMCs project.

Agency. Arguably, an interesting aspect of the sensorimotor and other embodied approaches is their agent-centredness. The problems of cognition are not addressed in general, externalist terms, but taking into consideration the agent's embodiment, situatedness, skills, and goals. The four kinds of SMCs could be placed in order along the dimension from external to agent's perspective of analysis.

The *SM environment* requires for its definition the least amount of detail about the agent. Because it only considers the open-loop sensorimotor regularities, it stays the same for all agents with the same (or sufficiently similar) sensors and effectors in a similar environment. The *SM habitat*, in contrast, takes into account the agent's internal dynamics and closes the sensorimotor loop. More details are required about the agent's constitution, this time by allowing its states to evolve in coupling with the environment. The *SM coordination* patterns bring on a task-oriented dimension in addition, by involving reliable aspects of the sensorimotor dynamics that contribute to functionality. Not only do we care about the agent's environment and internal dynamics, but also the tasks and survival constraints that the agent must fulfil. And finally, the *SM strategies* add a normative dimension with element of value for the agent (efficiency, dispositions, degree of skill, etc.).

The SM structures, thus, help mark the territory in which future work can link SMCT with a proper notion of agency as defined in (Barandiaran, Di Paolo, & Rohde, 2009). Accordingly, the three central requirements for speaking of proper agents are: 1) a notion of individuality, 2) a notion of asymmetry (agents sometimes do things in the world apart from being constantly coupled dynamically to the world) and 3) a notion of normativity (they do things in the world for reasons and these actions can fail, succeed or be placed on a scale of value). The open question that remains is how to link these ideas and the definition of agency provided in organizational terms (ibid.) with the progressive centrality of the agent's perspective in the four SM structures.

Temporality. Time plays different roles in each of these four kinds of SMCs. All of the structures can be time-dependent in the sense that external dependencies of time can alter both the environment and the agent (for instance, circadian and seasonal rhythms, or the effects of age and wear). Other than this, the *SM environment* is "atemporal": it describes all possible sensory consequences of freely introducing a motor change. The *SM habitat* involves the notion of bundles of trajectories. As such, it provides, as we have seen, dynamical information and introduces notions such as trends, attractor landscapes, oscillations, etc. *SM coordination* patterns entail a more "local" element of temporality than that of general trajectories and dynamical landscapes because they rely on the fine-grained exercise of specific agent-environment engagements with the added constraint of contribution to functionality. Elements of duration, rhythms, etc. become crucial for this contribution, e.g., oscillatory patterns different from those observed in our simulated agent around the narrow peak might not contribute to the task. Finally, *SM strategies* add to this latter aspect of temporality that of a temporal organization among SM coordination patterns. Efficiency, resilience or other normative evaluations will be affected by how patterns are coordinated in time, whether they run in parallel or in sequence, whether there are hard deadlines, delays, or dependencies, and so on.

Plasticity. In view of open questions on the organizational requirements for acquiring, modifying and sustaining eSMCs, it is worth raising the question of how the different SM structures can help classify different kinds of plastic changes and types of re-configurations that are able to support the acquisition of novel eSMCs, their progressive mastery and their change over time. Plastic reconfigurations can occur at different levels and involving all the different SM structures. However, we can attempt to draw some distinctions (it may not always be possible in concrete cases) by asking for each SM structure, what would be the *minimal* change that would be necessary for a re-organization of eSMCs to occur (leaving the global structure of the more general kinds of SMCs intact). Already this exercise helps us approximate a 'hierarchy' of plasticity going from the minimal to more drastic forms of change.

A minimal plastic change in the *SM strategies* can simply imply the re-organization (e.g., in time) of unchanged SM coordination patterns. This re-organization does not need to involve the acquisition of new SM coordinations, but simply an adjustment to the strategy with which they are used in order to improve, say, efficiency or robustness. In turn, plastic changes in patterns of *SM coordination* could imply only the fine-tuning of dynamical parameters so as to improve functionality, changing a skill, learning new tasks. Here, without any major re-organization of the regularities of SM habitat, some changes, e.g., tightening up the period and amplitude of an oscillatory pattern – such as those exemplified in our model for approaching a target in Section 2 – can count as sufficient for a plastic tuning of SM coordination patterns. Plastic changes in *SM habitat* can imply only the re-organization of internal dynamics (e.g., generating novel possibilities for action and perception) without alterations to bodily structures (e.g., damage to a sensor, or the incorporation of a tool or prosthesis). In contrast, plastic changes in the *SM environment* necessarily imply modifications to the body, the environment or both. Bodies change over time (growth, training, injury, old age) and the conditions of the environmental dynamics can change also (including as a consequence of the actions of the agent). Durable changes of these kinds directly alter the most basic SM structure (and will likely propagate onto the others).

6.2 Defining Habits and Skills

As highlighted in Section 3, the dynamical definitions of SMCs foreground the relevance of closed-loop dynamics for SMCT. Except in the SM environment, which is the most general kind of SMC (and consequently defines the broader constraints on the agent-environment system), there is a *co*-dependency between sensory and motor activity. This dynamic co-dependency of action and perception at various levels calls for the development of a concept for which this link is present from the start, and which allows the study of how this co-dependency may change over time, become stable or unstable, and organize behaviour in general. We argue that this is the notion of *habit*.

In Deliverable D1.1, we discussed the historical roots of the notion of habit and defended the view that this is a richer concept than normally thought. Traditional cognitivism has long belittled the notion of habit because of its rejection of behaviourist and associationist uses of this term. The central argument of this critique was that, unlike representational architectures, the behaviourist/associationist notion of habit could not provide a sufficiently powerful account of cognitive competence. As a result, the notion of habit as an elementary constituent of psychological theory collapsed into the behaviourist collection of associations between stimuli or between stimulus and response (a view that still pervades in contemporary computational neuroscience and machine learning approaches).

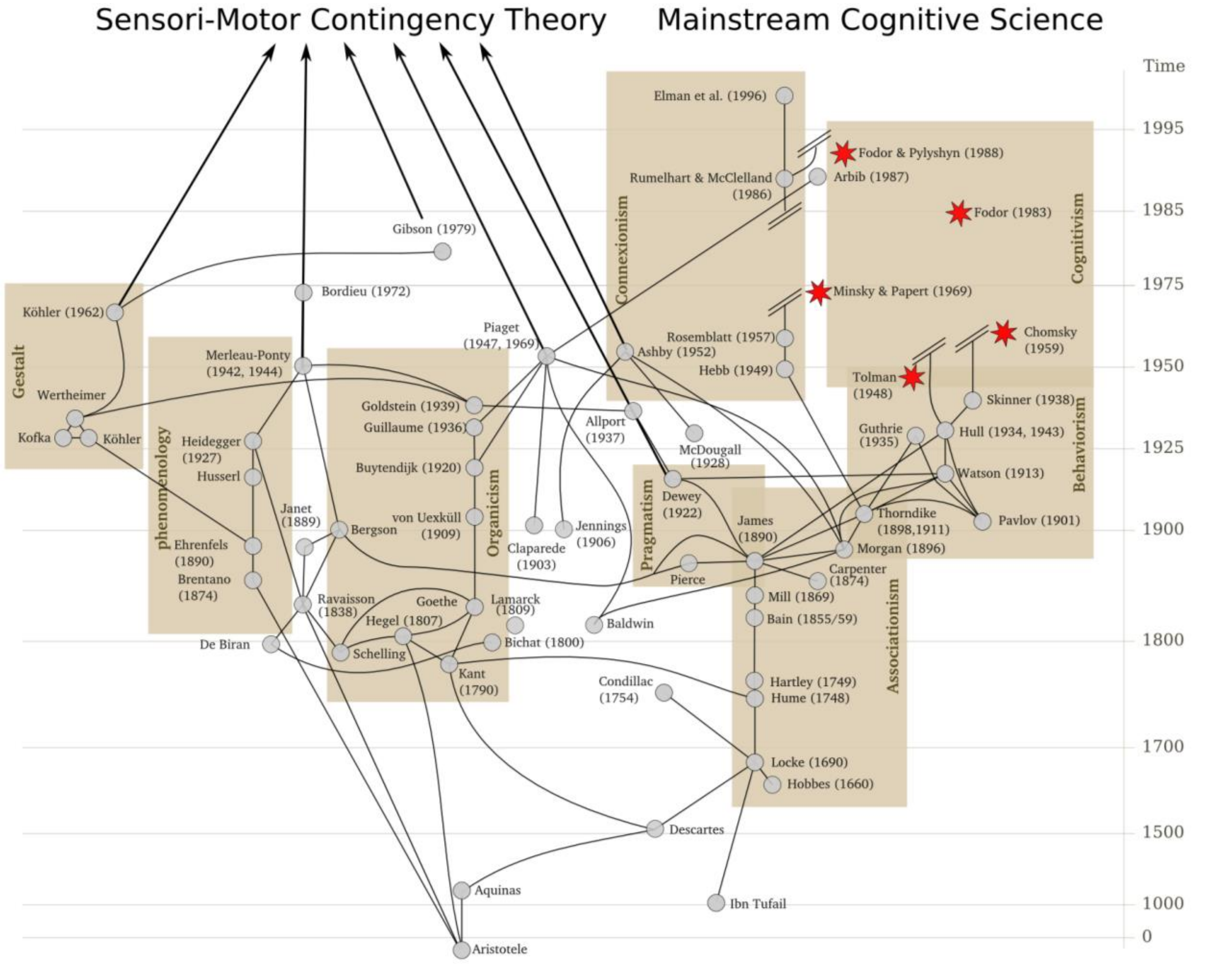

Figure 13: A genealogy of the concept of habit. For further details see text.

It turns out that the theoretical landscape previous to the behaviourist and cognitivist turns had a much richer notion of habit, particularly among pragmatists (James, 1890; Dewey, 1922) and in the Continental tradition (from Hegel to Ravaisson 1838, Guillaume 1936 and Merleau-Ponty 1942), (see Figure 13). It is this richer notion of habit that currently holds promise of becoming, if not a full-blown alternative to representations, at least a strong theoretical partner. Two key properties of habits might be said to sustain this promise. On the one hand, habits merge both actions and dispositions into a dynamic structure that cuts across the brain-body-environment boundaries. As a result, habits stand in a privileged theoretical position in the relationship between neural mechanisms and behaviour (without privileging either perception or action). On the other hand, habits are plastic, which allows them to cover a wide range of phenomena: from simple reflexes (very low plasticity) to different scales or learning and development, ultimately leading to the formation of flexible dependencies between them so as to get progressively structured into a complex organization.

We define *habit* as a *self-sustaining and plastic pattern of behaviour* that is formed when the stability of a particular structure of sensorimotor correlations is dynamically coupled with the stability of the mechanisms generating it.

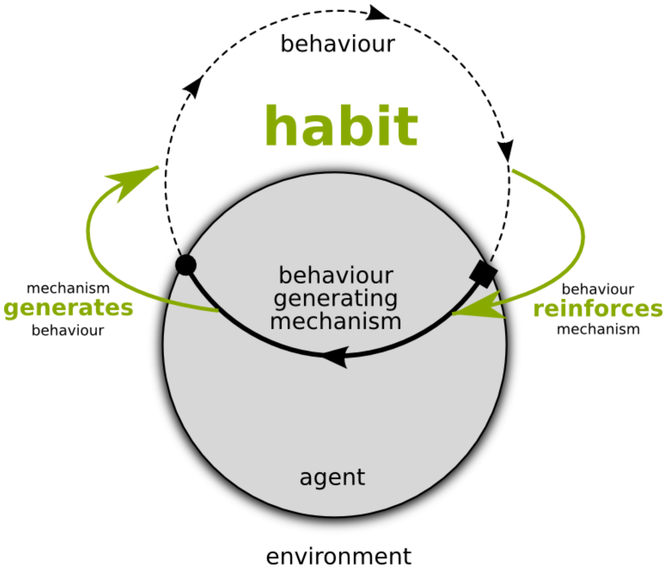

Figure 14. Representation of the dynamical definition of habit.

According to this definition (see Figure 14), once a habit is formed, its recurrence is a condition for its own contin-uation – the habit "calls" for its exercise and its exercise reinforces its permanence. One way of understanding this circularity is to say that the stability or recurrence of the behaviour that the habit involves (smoking, reading, jogging) both depends on and reinforces the mechanisms that give rise to it. Habits therefore imply plasticity. The notion of plasticity involves the capacity of a habit to be shaped or deformed under sensorimotor or neurodynamic "pressure" (meaning perturbations or variations on its stability conditions) and to maintain this deformation as its new form. In addition, plasticity is subject to different degrees and temporal scales as we have seen above and may involve different kinds of changes in the different SM structures.

It is important to note that we do not restrict the notion of habit to its common everyday sense. Looking at a handle just before we hold it to open the door and look forward right after, walking at a certain pace, breathing diaphragmatically, etc. are all examples of habits as much as smoking with a pipe or reading the newspaper on Sundays. Babies can be said to be born equipped with "innate" sen-sorimotor habits (mostly involving self--reinforcing patterns of stereotypical movements and corre-lated proprioceptive and tactile feedback) resulting from the exploration of sensory and motor spa-ces in the uterus (Kuniyoshi & Sangawa 2006). A process of self-

-organized development of habits and fixation of sensorimotor contingencies starts right after; always within an ecological context that provides stable regularities and remains open to the creation of new habits. Relevant here is Piaget's description of the transitions from reflexes to abstract sensorimotor schemas (Piaget, 1963). Habits do not stand in isolation as egotistically self--sustaining patterns of behaviour. On the contrary, as a result of inter-active development habits appear nested in a hierarchical and sequential manner. Many complex ac-tions are composed of webs of sensorimotor habits whose deep structure does not reveal itself until strongly disrupted. Such is the case, for example, in visual adaptation to inverted goggles reported by Ivo Kohler (1964), who points to the idea that "habits exist in all areas of human personality" (Kohler 1964: 137) and that only through a strong process of re-habituation "do we notice what habit is, and to what extent we consist of many and strong habits" (Kohler 1964: 138).

This notion of habit is preparatory for approximating a definition of the idea of *skill*, one of the most commonly used linkage terms in SMCT (together with related ideas such as "mastery" of the laws of SMCs). We conceive of skill as a 'projection' of a habit onto two dimensions. One dimension is associated with the agent itself as a mas-ter of the skill, and another to a classification of tasks and their associated normative framework.

Habits are best thought of as ecological structures involving the coupling with the agent and the environment. In contrast, the notion of *skill* is a convenient way of speaking of habits when we are concerned with projecting this larger notion onto the two dimensions just mentioned and when this projection is possible. Thus, we speak of skills as necessarily belonging to an agent and necessarily connected to an activity, the latter, in turn, being subject to a graded normative assessment (from clumsiness to mastery). In this way, while not legitimate for the concept of habits, it is indeed legitimate to speak of agent A's skill at performing task X with proficiency P in a normative framework F.

6.3 Dynamical definitions and kinds of eSMCs

As detailed in D1.1, we have identified three concrete extensions to the core notion of SMCs:

Modality--related eSMCs: This first type captures the specific changes of the sensory signal in a single modality depending on the agent's action. Examples are the different perspective distortions resulting from visual sensor movement and locomotion, sound pressure profile changes when the head rotates, and so on. This is the most basic type of eSMCs which, according to SMCT distinguishes the qualities of sensory experiences as "seeing", "hearing", "touching" etc., depending on the structure of the laws of SMCs.

Object--related eSMCs: The second type concerns the sensorimotor co-dependencies that are specific for each object under consideration, and are inherently supra-modal. Thus, they de-scribe the multi--sensory impression an object leaves upon a set of actions of the agent. An example is given by the different visual and force feedback signals received when touching a sponge, a piece of cardboard, or a piece of wood. This type of eSMCs identifies the object under consideration, and exercising actions from a set of object--specific eSMCs corresponds to perceiving this object. It is one of the fundamental claims of the approach pursued here, though, that the observed relations between actions and sensory changes are sufficient for recognizing a particular object. Object-specific eSMCs are more complex than modality-specific eSMCs since they necessarily involve a complex organization of the latter.

Intention-related eSMCs: The third type denotes a proposed novel generalization of the concept of SMCs and considers the long-term correlation structure between complex action sequences and the resulting outcomes or rewards. We propose that these intention-related contingencies capture the consequences of an agent's actions on a more general level and on extended time scales. This kind of contingencies can be the basis for action plans that involve several steps to reach an overall goal. Anticipatory behaviour and an ongoing sense of agency could be grounded in eSMCs.

Let us consider the relation between the four dynamical definitions of SMCs and the three kinds of eSMCs. First, it is important to notice that we are dealing with two different sorts of classification. On the one hand, the dynamical definitions remain at an abstract level with respect to task specificity. These SMCs should therefore be equally applicable to situations involving any modality, objects or intentions. On the other, the three eSMCs extensions point to concrete applications of the SMC concept to particular questions of relevance in cognitive science and neuroscience: integration across modalities, object recognition and manipulation, intention and action-planning. The two classifications therefore are complementary.

It should also be apparent that a full understanding of each kind of eSMC will likely involve aspects of the four SM structures. In other words, we do not expect any simple one-to-one mappings between the two classifications.

It is possible, however, to speculate about which dynamical SM structures are likely to be more central when approaching each of the three eSMCs. This examination can be done by applying to eSMCs the broad dimensions of temporality and agent-centredness used at the beginning of this section. Modality-related eSMCs are more general in terms of agent involvement than object-related eSMCs since the former describes general kinds of access to the world given a sensorimotor configuration (and a coupling with the environment), and the latter imply the deployment of specific sensorimotor patterns so as to constitute an object for the agent itself. In turn, object-related eSMCs are more general than intention-related eSMCs, since in addition to the agent activity required for the constitution of objects, intention-related eSMCs also involve aspects of motivation, planning and norms. In short, we require more knowledge about the agent for describing intention-related eSMCs than for object-related eSMCs. Although the classification is different, it is also true that, analogously, as we move from the SM environment to SM habitat, SM coordination, and SM strategies, we also require increasingly more knowledge about the agent.

A similar analogy could be drawn as we consider aspects of temporality. Modality-related eSMCs involve mainly the temporality of co-dependencies between sensor and motor patterns. Object-related eSMCs involve in addition the more complex aspects of temporal coordination between various modality-related co-dependencies. And intention-related eSMCs involve coordination across longer time-scales and the adaptive management of complex sensorimotor patterns, possibly involving various object-related eSMCs. Again, we have signalled earlier in this section an ordering for the dynamical kinds of SMCs along the complexity of temporality, and again the order goes from SM environment to SM habitat to SM coordination and SM strategies.

These comparisons suggest not quite a mapping, but at least a strong link between kinds of eSMCs and kinds of dynamical SMCs. It would be as follows. Modality-related eSMCs would most strongly relate to the SM environment and the SM habitat. They relate to the first, because they are strongly bound to the constraints of embodiment and to the second because they depend on the structure of closed-loop dynamics. Object-related eSMCs relate most directly to the level of SM coordination patterns and to some extent to short-term SM strategies involving the coordination of multi-modal co-dependencies. And intention-related eSMCs connect to longer-term SM strategies as both involve longer timescales and more complex organization of sensorimotor patterns, and in both notions there is an element of normativity.

This relation between classifications that have been formulated for different purposes and independently is telling, since it suggest that something that was missing in the original theory has been captured by these ideas, first by intuitive extensions to the notion of SMCs, and later by a dynamical operationalization of the various forms of sensorimotor co-dependencies.

7 Conclusion

The sensorimotor approach to perception has generated a lot of interest and debate by putting forward some strong claims about the embodied nature of perception and cognition. In this report we have placed this approach in the context of embodied cognitive science, and surveyed the various debates and unresolved questions. We then proceeded to offer solutions to some of these questions via conceptual developments, dynamical and probabilistic modelling, analysis and comparisons of different methodologies. By directly addressing what we considered the under-defined core of SMCT, namely the lack of operational definitions of SMCs, we have demonstrated that such a concept can indeed be operationalized (thus opening the road for further developments in theory, experiments and robot design). This process reveals that the notion of SMCs can actually be unpacked into four operational concepts (without implying these are the only possible ones), which we have examined empirically, and linked to other methodologies used in the project and to more general debates in philosophy of mind as well as the extended SMCs concepts or eSMCs.

In the context of this contribution, we have been able to progress two important themes. Firstly, understanding motor activity as not only enabling but also constituting perception. Secondly, showing that motor activity itself is co-defined by its role in perception. In this light we examined proposals for motor control based on internal models and found them wanting. A proposal based on sensorimotor co-definition seems to be empirically and theoretically stronger. We have completed this line of argument by a discussion of the theoretical, empirical and modelling evidence for the constitutive, not merely causal, role of sensorimotor coupling for cognition, thus answering various important criticisms of SMCT and suggesting that its proposals can possibly be understood in their more radical interpretation.

The result of this work is a more developed version of SMCT, but nevertheless a version that still needs work, as we have expressed in the last section. It needs to be systematically connected with various forms of cognition. It needs to provide models for the organization, acquisition, change, and integration of SMCs. And it needs to expand the set of conceptual tools and design and analysis techniques for capturing extended SMCs.

As such, we believe that the work described above significantly contributes to the theoretical development of the sensorimotor approach. We also believe that the work described serves the dual goals of both staying close to the spirit of the original formulation of SMCT by Noë and O'Regan, but also pointing the way to closer integration with the enactive cognitive science research programme launched by Varela and their co-workers while opening the way, of what has mostly remained a philosophical or theoretical position, towards its scientific and engineering development.

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