

A dynamical approach to the phenomenology of body memory: Past interactions can shape present capacities without neuroplasticity

Tom Froese^{1,2*} and Eduardo J. Izquierdo^{3,4}

¹ Institute for Applied Mathematics and Systems Research (IIMAS), National Autonomous University of Mexico (UNAM), Mexico City, Mexico

² Center for the Sciences of Complexity (C3), UNAM, Mexico City, Mexico

³ Cognitive Science Program, Indiana University, Bloomington, Indiana, United States of America,

⁴ School of Informatics and Computing, Indiana University, Bloomington, Indiana, United States of America

* Corresponding author: t.froese@gmail.com

Abstract

Body memory comprises the acquired dispositions that constitute an individual's present capacities and experiences. Phenomenological accounts of body memory describe its effects using dynamical metaphors: it is conceived of as curvatures in an agent-environment relational field, leading to attracting and repelling forces that shape ongoing sensorimotor interaction. This relational perspective stands in tension with traditional cognitive science, which conceives of the underlying basis of memory in representational-internal terms: it is the encoding and storing of informational content via structural changes inside the brain. We propose that this tension can be resolved by replacing the traditional approach with the dynamical approach to cognitive science. Specifically, we present three of our simulation models of embodied cognition that can help us to rethink the basis of several types of body memory. The upshot is that, at least in principle, there is no need to explain their basis in terms of content or to restrict their basis to neuroplasticity alone. Instead these models support the perspective developed by phenomenology: body memory is a relational property of a whole brain-body-environment system that emerges out of its history of interactions.

1. Introduction

Memory research has traditionally focused on our capacity to remember past events and to retrieve knowledge. And yet such forms of explicit recollection are just the tip of the iceberg: the vast majority of our past remains implicit and can no longer be recalled in terms of isolatable components. This implicit memory is shaped by our whole history of interactions in the world and by our interactions with others. It is at the core of how we can

act appropriately in the world without explicitly knowing how we are able to do so (Sutton and Williamson, 2014). We can refer to it as *body memory* because it is essentially through repeated embodied interactions throughout our life that we have acquired the various dispositions, skills, habits, and experience, which together constitute what we can do today (Summa *et al.*, 2012).

Building on the phenomenology of Merleau-Ponty, Fuchs (2012a, p. 86) defines body memory as “the totality of implicit dispositions of perception and behavior mediated by the body and sedimented in the course of earlier experiences.” This is a broad definition, so Fuchs (2012b) usefully distinguishes between types of body memory, including *procedural*, *situational*, *intercorporeal*, *incorporative*, *pain*, and *traumatic* body memory. Most recently, he has proposed additional types, namely *dyadic* and *collective* body memory (Fuchs, 2017). What all of these types of body memory have in common is that they are the means by which our past experiences implicitly shape our current sensorimotor engagements. Moreover, they all take as their starting point a phenomenological theory of the individual, which holds that an individual is fundamentally open to the world and to others, and all of the types therefore consistently stress the relational character of body memory (Summa *et al.*, 2012).

Relatedly, the enactive approach to cognitive science has started to generalise the relational character of memory from being a property of implicit memory to being a defining property of memory as such, including explicit forms of memory such as declarative memory (Hutto & Myin, 2017; Hutto & Peeters, in press; Loader, 2013). Instead these authors explore the possibility that remembering might be more productively conceived of as a certain type of interaction or activity, for example a reenactment.¹

This is a noteworthy convergence of research traditions: both phenomenological and enactive approaches reject the traditional cognitive science framework of memory, in particular its reification of the basis of memory into contents stored inside the brain (Fuchs, 2017, Hutto, 2016). However, both approaches require further clarification of the alternative, positive perspective. First of all, what can serve as the underlying basis of body memory, when body memory is conceived of as an active relational process, rather than as content located inside of an individual’s brain? And second, even if we accept that the basis of body memory can better described in relational terms, to what extent can this perspective be generalized to explicit forms of remembering? Our article aims to principally respond to the first question, but we hope that by doing so we also help to set the stage for possible responses to the second question, which we briefly consider in the discussion section.

Fuchs’ work provides an illustrative example of this lingering tension between the phenomenology of body memory, which conceives of the *phenomenon* itself in relational terms, and the traditional cognitive science of memory, which has restricted its underlying empirical *basis* to brain-based structural mechanisms like neuroplasticity. In an earlier article by Fuchs the explanation of the basis of an individual’s intercorporeal body memory is still given in traditional terms: “each body forms an extract of its past history of

¹ For a comprehensive enactive critique of the representational assumptions inherent in leading contemporary memory research, see Hutto and Myin (2017)

experiences with others that are *stored* in intercorporeal memory” (Fuchs, 2012b, p. 15; emphasis added). More recently Fuchs rejects as unfitting this *representational* view of mind and brain, according to which “the process of learning writes bits of information into memory banks where they are stored and can be recalled at will” (Fuchs, 2017, p. 336). However, whether we should also reject the traditional assumption that the basis of memory is *internal* to the brain, and thereby accept that other mechanisms apart from just neuroplasticity could also play a role, remains unclear.

For example, Fuchs (2017, pp. 336–337; emphasis added) affirms that, in the case of a skilled keyboardist who knows how to type without having explicit knowledge of the keys’ arrangement, the “memory is an emergent dispositional property of *the whole system of organism and keyboard connected to each other*” such that the “locus of this memory is *not* only in the brain”. Yet at the same time he concedes: “To be sure, this memory is based on specific patterns of neural activation derived from earlier experience”. This indecision resurfaces in Fuchs’ discussion of the underlying basis of dyadic body memory:

Where shall we localize this memory of joint dancing and other skillful or habitual interactions? On the one hand, the superordinate system or “extended body” of course has no natural substrate for forming a memory — it emerges only from the present connection of two bodies in which, based on each brain’s neuroplasticity, the respective dispositions have formed. *Each social memory must finally be based on the biological memory substrates of the individuals involved in order to become effective for their behavior.* On the other hand, the “open loops” of these dispositions are especially preattuned to the corresponding loops of the specific others. Only together are the individuals in a position to actualize and interenact their reciprocally related memories, which justifies attributing the memory as an emergent dispositional property to the dyadic system or the dyad itself. (Fuchs, 2017, p. 340; emphasis added)

Here we see Fuchs struggling to imagine how something as seemingly ephemeral as a shared history of reciprocal sensorimotor interaction *in itself* could become effective for shaping individuals’ behavior. Ultimately, despite his rejection of the representational stance of the traditional framework, he therefore falls back on the notion that the basis of dyadic body memory, and presumably of body memory more generally, is only to be found in an individual’s internal biological memory substrate. This keeps his phenomenological proposal tied to the rather restrictive traditional theory that all memory is finally based on neuroplasticity, even if he rejects its representational interpretation. Accordingly, the much more radical possibility suggested by the phenomenology of body memory, namely that the basis of this memory might itself be relational and directly realized in our interactions in addition to neuroplasticity, remains unexplored. It seems that in the end this novel possibility was replaced by the more conservative idea that our interactions simply enable the shared actualization of two distinct body memories whose basis is restricted to the brain of each individual.

We propose that a fruitful way to resolve this tension between phenomenology and cognitive science is to rethink the latter’s approach to memory. In particular, we need to replace the traditional focus on information encoding, storage, and retrieval with an enactive focus on remembering as a type of action or activity that is inherently interactive and relational (Hutto, 2016; Hutto & Myin, 2017; Hutto & Peeters, in press; Loader, 2013).

However, while it is relatively straightforward to think of structural changes in the brain as being effective for behaviour even if we do not consider these changes as encoding content, it is much harder to move beyond the restriction to changes in brain structure altogether. What is needed are something akin to Dennett's intuition pumps: conceptual tools that help us to overcome our traditional intuitions about what must be the necessary basis of memory for it to be effective for behaviour. As we will show in detail, the models have already begun to reveal the different ways in which an agent's memory-dependent capacities can be fully constituted by its history of interactions – potentially even in the complete absence of neuroplasticity. The models illustrate that, when it comes to thinking about the basis of body memory, the traditional framework is not the only game in town: their analysis demonstrates that the use of representational metaphors is unnecessary, and that an *a priori* restriction to the brain as the only possible basis is counterproductive.

The rest of this article is structured as follows. In section 2 we take a closer look at the phenomenology of body memory, focusing on four key types. In section 3 we present three embodied cognition models to illustrate how these four types could have a relational dynamical basis. In section 4 we discuss the implications of these models and point to directions for future research.

2. The phenomenology of body memory

Body memory has been an important topic in the phenomenological tradition of philosophy, especially in the work of Merleau-Ponty. He saw it as an important middle ground between the classical dichotomy between the conscious and the unconscious, offering phenomenology a way to systematically address features of mentality that are not directly present to consciousness (Phillips, 2017). In contrast to the still common assumption that the unconscious is contained *inside* the individual, he proposed that it is actually spread out *between* the individual, the world, and the others. Accordingly, Merleau-Ponty notes:

This unconscious is to be sought not at the bottom of ourselves, behind the back of our “consciousness,” but in front of us, as articulations of our field. It is “unconscious” by the fact that it is not an *object*, but it is that through which objects are possible, it is the constellation wherein our future is read. (Merleau-Ponty, 1964/1968, p. 180)

This description of how the unconscious can be effective for behaviour matches the specific case of body memory, which also tends to be described in terms of spatial metaphors. For example, Merleau-Ponty (1964/1968, p. 180) talks about the “articulations of a field”, a metaphor further developed by Fuchs (2012a, p. 91) in his investigations of the “structures” of the “relational field” that body memory constitutes. Importantly, this field is not restricted to the physical body. Rather, past experiences are said to “blanket the environment like an invisible network which relates us to things and to people” (Fuchs 2012a, p. 91). Fuchs (2012a, p. 92) therefore argues that, given that body memory “constitutes a sensomotoric, libidinous and interactive field in which we, as embodied beings, constantly move and conduct ourselves”, its phenomenological analysis should be complemented from the side of the person's environment. The space around the individual is not a neutral physical space; rather, it is a lived space “permeated by tangible *field*

forces’ or *‘vectors’*, in the first place those which attract and repel” the individual (Fuchs 2012a, p. 92).

These metaphorical descriptions of body memory and lived space, namely in terms of a relational field that contains attracting and repelling structures, are loosely based on the classical conceptual apparatus of the natural sciences. In other words, even though lived experience is not a directly measurable variable, unlike say gravity, the intuitive application of dynamical metaphors suggests that dynamical systems theory could still be useful for sharpening phenomenological accounts of body memory and lived space by grounding its metaphors.

Unfortunately, however, the task of providing dynamical accounts of real brain-body-environment systems continues to be a highly challenging enterprise, even for the simplest animals (Izquierdo & Beer, 2016). In the next section we will therefore employ simulation models of minimal examples of embodied cognition, sometimes called “minimal cognition” models, as conceptual tools to inform our theoretical understanding of the basis of body memory. In particular, the aim is to clarify the possible dynamical basis of Fuchs’ (2012b) three most fundamental types of individual body memory, i.e. procedural, situational, and intercorporeal body memory, as well as of Fuchs’ (2017) most fundamental type of social body memory i.e. dyadic body memory. Note that this differentiation into types should not be misunderstood as demarcating distinct phenomena; rather, the types help to highlight different aspects or manifestations of body memory as such, and in most ordinary situations they are presumably all effective at the same time.

The phenomenology of these fundamental types of body memory can be briefly characterised as follows:

1. *Procedural body memory*: This type of body memory constitutes our capacity of knowing how to do things, such as walking, cooking, or playing the guitar (see also Sutton & Williamson, 2014). It consists of sensorimotor and kinesthetic faculties that are “realized in dynamical processes: patterned sequences of movement, well-practiced habits, skillful handling of instruments, as well as familiarity with patterns of perception” (Fuchs, 2012b, p. 12).
2. *Situational body memory*: This type of body memory extends to the spaces and situations in which we tend to find ourselves, and it can therefore also be considered as a form of spatial memory. But situations are not just spatial in a neutral way; phenomenological reflection reveals that they are “holistic inseparable units of bodily, sensory, and atmospheric perception” (Fuchs, 2012b, p. 13). This type of memory helps experienced persons to immediately recognize what is essential or characteristic of a complex situation.
3. *Intercorporeal body memory*: The term “intercorporeality” was introduced by Merleau-Ponty (1960/1964) to describe the pre-reflective, embodied, mutual understanding that is inherent in normal encounters between people (Moran, 2017). This type of body memory captures the significant extent to which our embodied interactions with others are shaped by previous encounters, going back to formative

developmental experiences. To some extent it is a combination of the previous two types of memory: it is a procedural memory that is specific to situations involving others.

4. *Dyadic body memory*: This type of body memory is like intercorporeal memory in that it is also shaped by an individual's history of interactions with other people. However, it is no longer a property of that individual, but is distributed across two persons in interaction. Dyads can form one "extended body" (Froese & Fuchs, 2012) during interaction by dynamically integrating their motor systems to form one joint procedural field with its own history and capacities. A paradigmatic case is a social interaction that takes on a life of its own, such as a jazz improvisation duet (Torrance & Froese, 2011).

These characterisations, although brief, highlight the rich phenomenology of the various types of body memory, and we do not pretend to be able to address all of their nuances in the following analyses. Instead we will focus on some of their most essential properties:

- The capacity of knowing how to do things based on patterned sequences of movement (procedural body memory)
- The inseparability of procedural body memory from its spatial context (situational body memory)
- The capacity of knowing how to do things based on patterned sequences of interaction with others (intercorporeal body memory)
- The inseparability of intercorporeal body memory from its social context (dyadic body memory)

We will consider the tension resulting from modeling these properties of body memory as if they were part of a completely deterministic dynamical system in the discussion section, where we will also consider the challenge of generalizing our dynamical analysis to more explicit forms of remembering.

3. A dynamical approach to body memory

Our aim in this section is to clarify what could be involved in giving a dynamical account of the basis of body memory, and to do so with the help of detailed simulation models rather than just metaphorically. In particular, we will demonstrate that in principle there is no explanatory need to fall back on the traditional framework of storage and retrieval of representational content. Of course we do not deny that there exist a host of structural changes in real brains, such as neuroplasticity, and that these play essential roles in memory formation. Rather, we see no need to interpret these changes in representational terms, and instead prefer to treat them as part of a broader history of agent-environment interaction. In order to clarify the role of this interaction process *per se* we will employ the models to illustrate how a history of interaction may be sufficient to serve as the basis of essential properties of body memory, even without being accompanied by any structural changes inside the agent. Consequently, it should become easier to rethink the empirical basis of real body memory in a relational manner, even if it is the case that actual agent-

environment interaction is always also accompanied by structural changes in the agent's brain.

We will describe three case studies from our own work. Given that all of them employ a similar methodology, we first describe it briefly here in general terms. The interested reader can consult the original publications for details. All three case studies used a computer-based simulation modelling approach for studying behaviour and cognition, which takes seriously a situated, embodied, and dynamical perspective (Beer, 2014; Harvey *et al.*, 2005). There are three main components to the approach.

First, a task is chosen that allows one to study the simplest behaviours that raise issues of interest for cognitive science. This includes designing an agent with a body that can move in order to actively sense and explore its environment.

Second, an artificial neural network is chosen to serve as the agent's brain that is capable of rich, nonlinear, multi-timescale dynamics, and whose parameters can be tuned to produce different behaviours.

Third, we use an evolutionary algorithm to automatically explore the space of parameters to search for a configuration that produces the desired behaviour, but without constraining how it is implemented. The main motivation for this is to minimise the danger of building into the model our preconceptions of how an agent must solve the task. Running the evolutionary algorithm multiple times, starting with different initial conditions, allows one to systematically explore the space of potential solutions to the task. We generally find that the agent's neural network ends up exploiting its embodiment and situatedness because this tends to reduce the complexity of the task.

This approach comes in many varieties and has been applied to a wide range of tasks (Bongard, 2013; Nolfi *et al.*, 2016; Vargas *et al.*, 2014). It is important to be clear that we do not assume that this kind of synthetic investigation is equivalent to phenomenological investigation or psychological experimentation. Its results are neither direct insights into our lived experience, nor are they empirical data. Rather, the purpose of such a synthetic study is to serve as an "opaque thought experiment" (Di Paolo *et al.* 2000) that helps to make our assumptions explicit and to question our intuitions. In this sense the field's emphasis on the systematic exploration of an imaginary space of 'life-as-it-could-be' is somewhat reminiscent of the phenomenological method of free imaginative variation, albeit one supplemented by technological means in order to overcome the complexities involved in imagining living and cognitive systems (Froese & Gallagher, 2010).

The case studies are organised in terms of their increasing conceptual distance from the guiding assumptions of the traditional framework of memory research, with the aim of helping to free our intuitions from its constraints. We begin by challenging the standard assumption that the basis of body memory must be based on structural changes inside an individual's brain (case study 1). Then we go a step further and demonstrate that in principle the basis of body memory does not even necessarily depend on neural dynamics at all (case study 2). And finally we show that there is no a priori reason to limit this basis to the biological substrate of an individual's body (case study 3). We hope that by the end of

this series of case studies the reader will feel more confident in conceiving of the basis of body memory in nonrepresentational, relational terms.

3.1 Case study 1: Body memory beyond neuroplasticity

This embodied cognition model was reported by Izquierdo (2008), based on an earlier model by Izquierdo-Torres and Harvey (2006); an extension of the task was studied by Williams, Beer, and Gasser (2008). The original model involves a task in which successful object categorisation requires taking a past event into account. A visually guided agent is presented with two circles, one after the other, separated by a time-delay. The agent must catch the second circle if it has the same size as the first circle and avoid it otherwise (Figure 1). The agent’s neural network is devoid of neuroplasticity, so that the basis of their capacity to solve the task cannot rely on structural changes in their artificial brain.

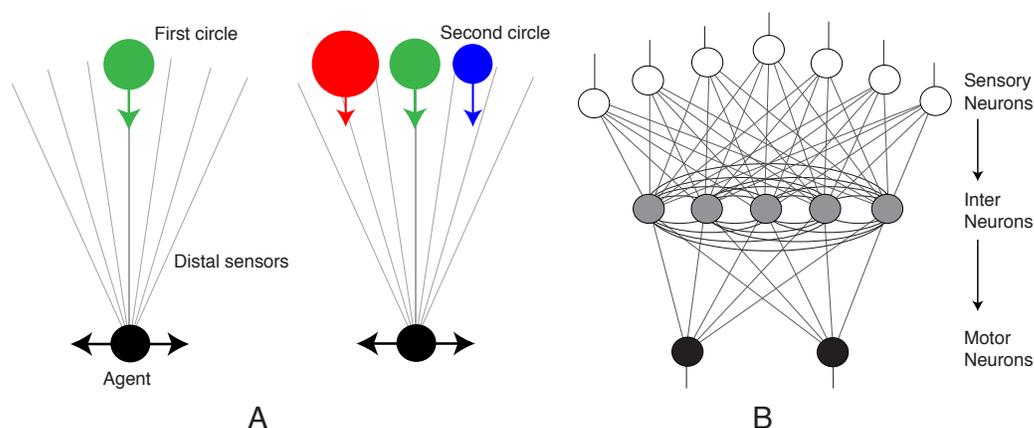


Figure 1. Environment and agent setup of categorisation task. (A) The agent (black circle) can move horizontally while circular objects of different sizes (coloured discs) fall from above. The agent has an array of seven distal sensors (grey lines). Its task is to categorise the second circle as having the same or different size as the first circle. (B) The architecture of the recurrent neural network consists of a layer of seven sensory nodes connected to a layer of N interneurons, which are in turn connected to a layer of two motor neurons. The interneuron layer is fully interconnected, including self-connections. Artificial evolution was applied to networks with different N , ranging from three to six. Figure adapted from Izquierdo (2008).

From the perspective of the classical approach to memory, it might be expected that a successful strategy would involve remaining stationary as the first circle falls, sensing its course passively while ‘encoding’ its size in the neural network. However, this is not what was found². Analysis of successful agents revealed a different strategy: agents did not remain stationary; instead they move while sensing the falling circle (Figure 2, A and B). Importantly, the movement is not irrelevant to the learning process. Specifically, agents move farther away from bigger circles than from smaller circles. As a result of this movement, the second circle starts to fall in a position relative to the agent that is dependent

² To be fair, given that the artificial neural networks were designed to lack neuroplasticity for illustrative reasons, there was no possibility that a more traditional solution based on structural changes could have evolved. However, we know from previous work in evolutionary robotics that even if neuroplasticity is a possible mechanism this does not entail that the evolutionary algorithm would have exploited it as the basis for memory formation (Ziemke and Thieme, 2002).

on the first circle's size. Accordingly, the agents exploit their relative distance to the second circle, once it appears, as a cue of the size of the first circle, which can help them to categorise the two circles as identical or different in size.

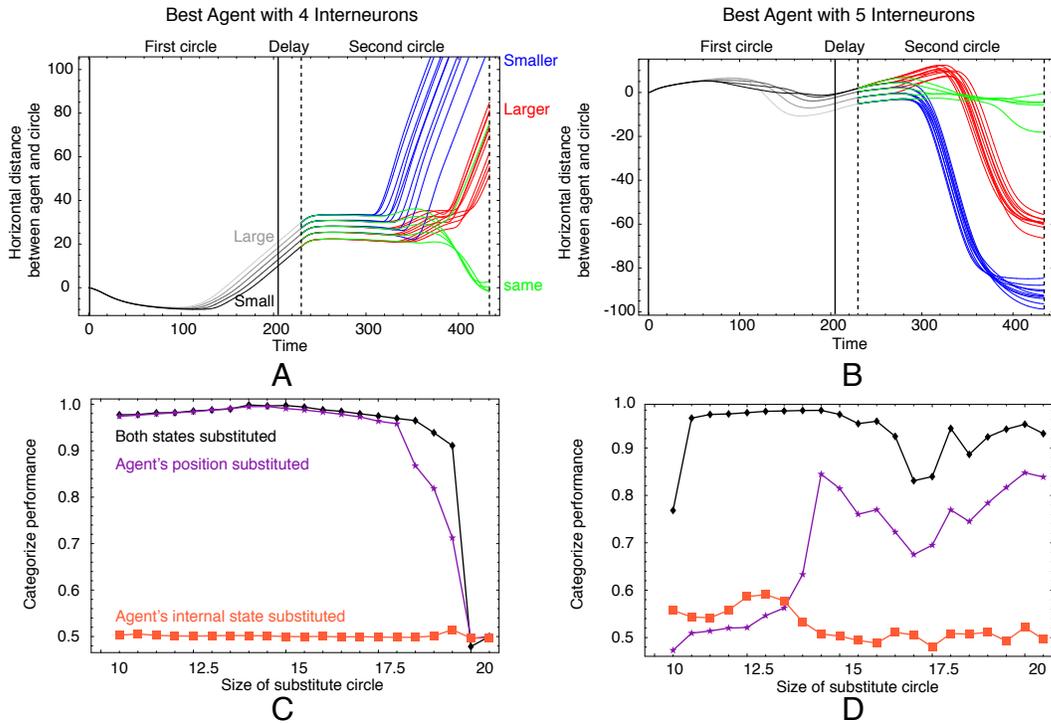


Figure 2. Categorisation behaviour of the best agents with four (left) and five interneurons (right). (A and B) Agent trajectories in object-centred coordinates. The two solid vertical lines denote the start and end of the first phase, when the first circle is falling. Trajectories are shown for circles of five different sizes. The two dashed vertical lines denote the start and end of the second phase, when the second circle is falling. Trajectories are now shown for 25 conditions: five sizes of the second circle for each of the five sizes of the first circle. Green, blue, and red trajectories correspond to second circles that are identical, smaller, and larger, respectively. (C and D) Each point corresponds to the performance (vertical axis) of the agent at approaching circles that have the same size as that of the substituted circle (horizontal axis) and avoiding those that are different. Three conditions are shown: when only the agent's position is substituted (purple); when only the agent's internal state is substituted (orange); and when both are substituted (black).

Focusing on the best agents with neural networks containing interneuron layers with four and five neurons, the first thing to note is that they both managed to solve the task consistently (Figure 2, A and B). Moreover, although agents were only selected for their capacity to categorise the two circles as either the same or different in size, a capacity for categorising smaller-than-the-first and larger-than-the-first circle also emerged. This finding already shows that their strategy, whatever its basis may be, must be quite flexible; the agents would have no problem solving tasks involving comparisons of size other than just in terms of identity and difference.

But what is the basis of this capacity? Does the agent have in its internal state all that is required to be able to categorise circle sizes during the fall of the second circle? Or does this capacity rely only on the agent's history of interactions with the first falling circle? Or is it a mixture of both internal and relational aspects?

Izquierdo (2008) addressed these questions with the following experiment: before the fall of the second circle different aspects of the brain-body-environment system were substituted with what they would have been, if the agent had originally encountered a substitute first circle of a certain size, which was different from the original first circle. Performance was measured in relation to the substitute first circle (Figure 2, C and D). Three conditions were examined. In the first condition, the position of the agent's body with respect to the second circle was substituted, which amounts to a substitution of the body-environment relational state. In the second, the full internal state of the agent, i.e. activations of all the neurons, was substituted. In the third condition, both the relational state and internal state were substituted. This last condition corresponds to a complete substitution; it effectively erases all possible influences of the interaction with the originally presented first circle and thus corresponds with what would be the normal performance after having encountered a first circle with the substituted size. We highlight several take-away messages of this experiment.

First, and most importantly, the history of interaction with the first falling circle consistently plays a role in categorisation performance. In fact, the agent with four interneurons relies almost exclusively on its relational state: just changing its relative position, regardless of what the state of the neurons are, will change the whole 'memory' of the system (Figure 2, C). This can be observed from the similarity between the performance when only the agent's position is substituted (purple) to when both are substituted (black), and the near random performance when only the internal state is substituted (orange). The prevalence of strategies in which the relational state played a role suggests that evolution will tend to exploit such body-environmental regularities when available, even if a purely internal solution could also exist in principle.

Second, the contributions of the relational state and internal state do not have to be linearly additive: performance after substituting either the relational state or the internal state does not necessarily add up to normal performance when both are substituted simultaneously. This is most evident in the example of the agent with five interneurons for small circles: performance after substitution of just the relational state, or of just the internal state, is only marginally better than mere random behaviour. Yet when both are substituted together there is a large increase back to normal performance. What we see is an emergent effect of the interaction between the agent's relational state and its internal state, where the combined effects are greater than the sum of the separate parts.

Third, the effect of the relational state versus that of the internal state was not only different for every agent that was examined, but it was also different in the same agent for different ranges of circle size. For example, the agent with five interneurons relied much more on the relational state for circles of bigger sizes. A rough analogy of this finding in the context of human memory could be the use of an incomplete shopping list or notebook: items that are harder to remember are externalised by writing them down, while the other items are remembered largely on the basis of internal neural dynamics.

Fourth, the existence of a correlation between the internal state and the external feature to be remembered does not necessarily entail that this correlation is actually exploited by the agent. For instance, in the agent with four interneurons the neuron activations show a high

degree of correlation with the size of the first circle (0.98 Pearson correlation). However, despite such an impressive level of correlation, the manipulation experiment reveals that this internal state does not play an important role in the agent's process of categorisation: substituting it has no or little effect on improving performance. This provides a clear warning of the danger of overreliance on the discovery of correlations between inner and outer states to understand the remembering process, a danger already highlighted by previous robotic approaches to memory (e.g. Ziemke & Thieme, 2002), and by recent enactive critiques of representational interpretations of the discovery of place cells, grid cells, etc. in the rat brain (Hutto & Myin, 2017, pp. 239–240).

In summary, there are three main lessons to be drawn from this case study:

- 1) We should expect body memory to opportunistically incorporate body-environment relational state in practice, even if an alternative strategy based only on internal state may also be possible in principle.
- 2) The existence of a correlation between an individual's internal state and an aspect of their environment to be remembered does not entail that this correlation will be exploited in their remembering.
- 3) Even if this kind of correlation forms part of the basis of an individual's capacity to behave in a history-dependent manner, this does not make it necessary or even useful to explain this capacity in terms of content.

These lessons support key claims of the enactive approach, which conceives of the basis of memory as primarily extended and contentless (Hutto & Peeters, in press). Paraphrasing Brooks' (1991) famous slogan, it turns out that it is often better for the agent to use its history of sensorimotor interaction as its own best memory. This combination of an enactive and dynamical approach to memory therefore also promises to provide a more fitting theoretical partner in cognitive science for phenomenology's relational conception of body memory. In the next two case studies we will further strengthen this link.

3.2 Case study 2: *Body memory beyond the brain*

The first case study demonstrated that having a history-dependent capacity does not require neuroplasticity. However, it might be argued that this result does not challenge neurocentrism directly, because it still leaves open the possibility that the underlying basis of this capacity is limited to its neural activity, while body-environmental relations only play a secondary, contextual role. In other words, it still remains to be confirmed that an agent's history of sensorimotor interaction *in itself* could constitute the basis of its history-dependent capacity.

One way of clarifying this more radical possibility is to model an embodied agent with a reactive internal system that completely lacks internal state, such as a purely feed-forward neural network, and then evaluate its performance on a task whose solution requires non-reactive behaviour. A *reactive* system is one whose outputs are at each moment only determined by its current inputs. Even though no actual living system is reactive in this

strict sense, the goal of this example is to clarify an important point: whether a history-dependent capacity could arise in an agent without any internal basis for memory, not even based on the short-term neural dynamics that played a role in some conditions of case study 1. If so, this would imply that the agent’s sensorimotor history *as such* could also serve as the basis for this capacity.

A suitable model was reported by Izquierdo (2008), based on an earlier model by Izquierdo-Torres and Di Paolo (2005). The task was defined in terms of the task classifications introduced by Clark and Thornton (1997). Performance on a “type-1” task only requires the agent to exploit regularities in the current input. In robotics, light-seeking and obstacle avoidance are typical type-1 tasks. In contrast, “type-2” tasks also require the exploitation of regularities that are not directly given in the current input. Accordingly, Izquierdo treated successful performance on a type-2 task as involving a form of *non-reactive* behaviour.

An appropriate type-2 task is catching an object under visual inversion (Figure 3). A visually guided agent is presented with a falling circular object, and its task is to catch the object by centring its body under the object. Objects vary in size and in location. The agent has to catch the object under both normal vision and left-/right-inverted vision. The effect of inversion is that an object that appears to the right of the agent will in fact be to its left, and vice versa. This is a type-2 task because it requires that the agent is capable of responding differently to the same stimuli depending on the context (i.e. normal vs. inverted condition).

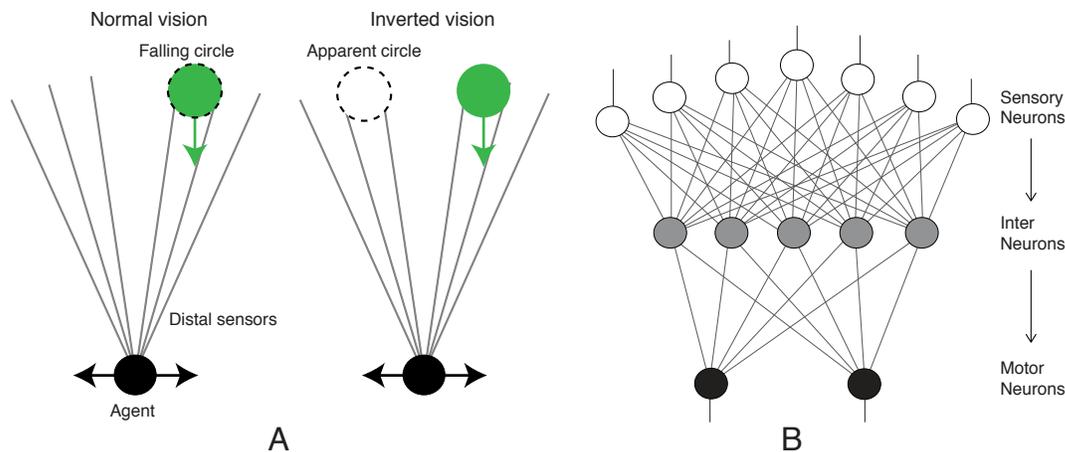


Figure 3. Environment and agent setup of visual inversion task. (A) The agent (black circle) can move horizontally while a circular object (green disc) falls from above. The agent has an array of six distal sensors (grey lines). When sensors are inverted, an object falling on the right-hand side of the agent is sensed with its left sensors, or vice versa, making the object appear as if it were on the opposite side (dashed circle). (B) The architecture of a feed-forward neural network consisting of a layer of six sensory neurons connected to a layer of five interneurons, which are in turn connected to a layer of two motor neurons that control the agent’s horizontal movement. The network architecture is symmetrical. None of the neurons has internal state. Figure adapted from Izquierdo (2008).

This problem could be easily solved by an internal mechanism that takes into account the agent’s history of interaction, i.e. by noting whether moving toward the object actually had the desired effect of reducing its distance, and if not, adjusting future behaviour based on this past experience. However, by assigning a reactive neural network to this agent, this

kind of solution is prohibited because the agent has no internal state that could keep track of its past. In this way we are able to verify whether an agent's type-2-task-solving capacity can be directly based on its history of sensorimotor interaction. And indeed, despite the imposed restriction to a reactive neural network, the evolutionary algorithm reliably found configurations of this neural network that allowed agents to catch falling objects with normal and inverted sensors.

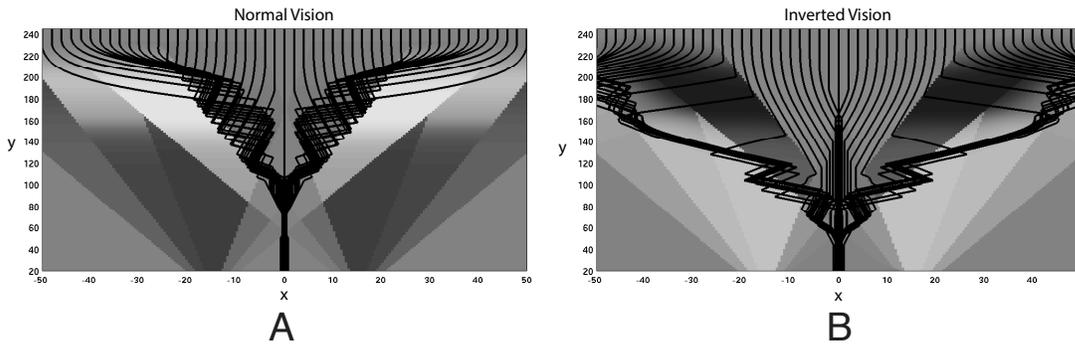


Figure 4. Movement trajectories superimposed on velocity tendencies for normal (A) and inverted (B) vision. The x-axis and y-axis represent the horizontal and vertical distance between the agent and the falling object, respectively. The background shading indicates whether the agent is approaching (light) or avoiding (dark) the actual horizontal location of the object. The magnitude is represented by the intensity of the shade (mid-grey means no agent movement). Figure adapted from Izquierdo (2008).

Figure 4 shows behavioural trajectories of the best agent when catching objects using normal and inverted sensors. Notice that, as a result of the agent's reactive neural network, the background shading representing the velocity fields in the two conditions is also inverted: in the inverted vision condition an object that would normally cause the agent to, for example, approach it, would now make it move in the opposite direction. Conversely, a correctly sensed object and a wrongly sensed object that happen to appear, from the agent's perspective, in the same position will cause the same instantaneous movement towards the object's apparent location. Yet overall the history of interaction of the agent results in behavioural trajectories that always lead them to successfully catch both correctly and wrongly sensed objects. How can this be possible?

In the normal condition, trajectories first rapidly move to the centre until the velocity field turns slightly divergent and then remain trapped by bright regions of centring velocities, which eventually converge on the object's horizontal position. In the inverted condition, trajectories that start close to the object move closer because of the centring velocities of the central field. Other trajectories initially move away from the centre, only to be trapped in a different and wider convergent region, reaching the centre at a later stage when the divergent fields are no longer effective. This particular strategy, which is just one among several discussed by Izquierdo (2008), takes advantage of the agent's multiple sensors. In the normal condition the agent moves closer and keeps the object fixated with its inner sensors, while in the inverted condition it moves away until it can keep the falling object fixated with its outer sensors. Thus, although the agent cannot know whether it is operating in the normal or inverted condition, the end result is the same: the agent catches the object. It can do so on the basis of giving rise to different histories of interaction in the two conditions.

A general lesson to be drawn from this case study is that we cannot deduce the limitations of an individual's behaviour only from knowing the limitations of its brain. Moment by moment, the agent responds reactively, but as a result of the history of interaction with its environment, the agent is capable of solving a task that requires it to have some form of memory or state. However, it achieves this by exploiting the state arising from its sensorimotor loop. The agent modifies its position with respect to the object, and thereby partially determines the sensory pattern it will receive next, which in turn will determine how it is going to move next. As such, the agent's present movement is indeed dependent on its past, but on a past that is inherent in its relationship with the environment. This result confirms what we had already suspected, namely that in some cases the agent's history of sensorimotor interaction can serve as its own best memory.

3.3 Case study 3: Body memory beyond the body

The previous two case studies have demonstrated that in principle an agent's history-dependent capacities can have a relational basis that is determined by its history of interaction, and even exclusively so if necessary. The key insight is that when we conceive of behaviour as a relational agent-environment property, as the dynamical approach proposes, then we no longer have to follow the traditional approach in assuming that the past's effectiveness for current behaviour can only be based on changes that are internal to an individual. This insight opens up new possibilities for thinking about the potential basis of body memory in situations that involve interaction with other agents.

Social interaction is of course a paradigmatic example of a relational behavioural phenomenon. This is confirmed by a series of modelling and psychological studies that lead us to conceive of the process of interaction between two individuals as an emergent property of one integrated brain-body-environment-body-brain system (Froese, in press; Froese, Iizuka & Ikegami, 2013). This idea is illustrated in Figure 5.

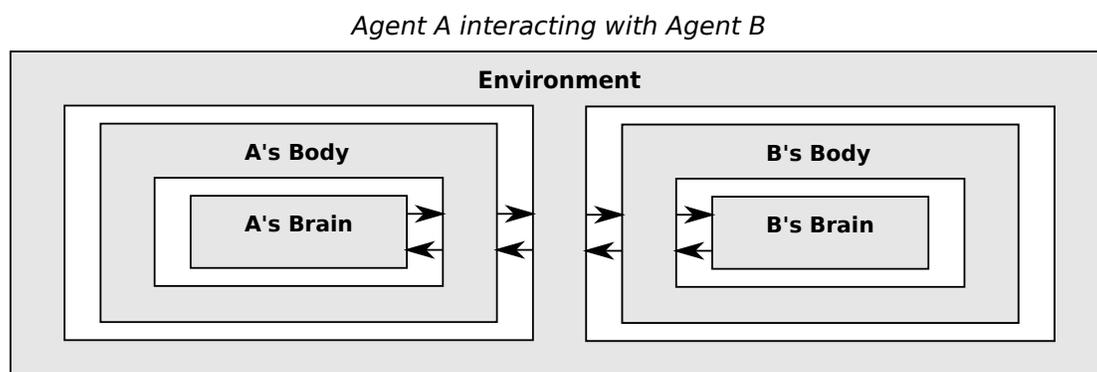


Figure 5. A dynamical approach to interaction between two embodied agents. An agent's nervous system (abbreviated as "brain"), body, and environment are conceptualized as nonlinear dynamical systems that are coupled, thus forming an irreducible whole. When agent A is interacting with agent B, their coupling constitutes a whole brain-body-environment-body-brain system. The illustration was originally published by Cambridge University Press in: Froese, Iizuka, and Ikegami (2013). From synthetic modeling of social interaction to dynamic theories of brain-body-environment-body-brain systems. *Behavioral and Brain Sciences*, 36(4), pp. 420-1; reproduced with permission.

From this dynamical perspective it seems reasonable to expect that a shared history of interaction between two agents will not only shape their individual body memories, but that, moreover, this shared history in itself will also shape their present social interaction. We will illustrate this possibility with another embodied cognition model.

Froese and Fuchs (2012) describe a model, originally reported by Froese and Di Paolo (2008) and based on a model by Iizuka and Di Paolo (2007), in which two agents are embodied in an open-ended 1D space along which they can move left- and rightwards. One agent is oriented upward and the other downward. Each agent is equipped with a touch sensor that protrudes from the centre of their body, and which becomes active when it is overlapping the body of the other agent and remains turned off otherwise. The touch sensor is connected to a fully interconnected neural network consisting of three neurons, two of which modulate an agent’s left- and rightward velocity. The structure of each agent’s neural network was the same. The task consists of making contact with each other as far away as possible from their starting positions. This involves initially finding each other, negotiating a shared direction of movement (requiring symmetry breaking, since one agent’s left is the other’s right), and finally jointly moving toward the chosen direction while making sure to stay in contact. The model setup is illustrated in Figure 6.

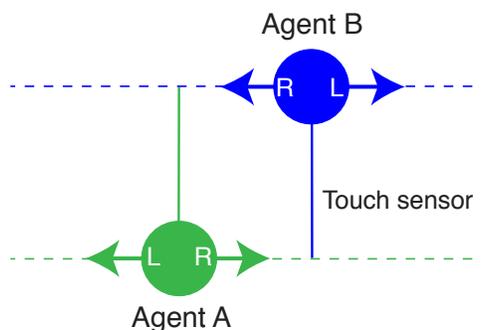


Figure 6. Environment and agent setup of the social coordination task. Two agents are placed in an open-ended 1D environment facing each other, so that one agent’s left-hand (L) is the other agent’s right-hand side (R). They are capable of moving left and right in a continuous manner. They have a touch sensor extending from the middle of their body. Their task is to touch each other as far away as possible from their initial positions, which requires negotiating a common direction.

The best pair of agents was analysed in order to understand how they achieve their joint performance. To understand how the neural network modulates an agent’s behaviour, it is helpful to focus on a subsystem consisting of the two motor neurons. It turns out that when the touch sensor is fixed to be either on or off, neural activation always converges on a single stable attractor from any initial condition. However, the position of this attractor in internal state space and the structure of its basin of attraction differ depending on the state of the sensor. In other words, the touch sensor has the effect of dynamically reorganising the structure of the neural network’s motor subsystem, such that sensing cannot be considered as separate from the way in which the agent’s movement is realised.

This sensorimotor interdependence at the individual level also explains why an agent’s motor subsystem behaves very differently when the agents coordinate their sensorimotor interaction: it opens up each agent to the possibility of having their neural network

reorganised by the other. The agents evolved to make use of this possibility for co-determination such that during reciprocal interaction an agent's neural activity enters into a cyclical pattern in one of two distinct regions of neural state space, with one region corresponding to leftward, the other to rightward overall joint movement. This emergent pattern of neural activity is what permits an agent to oscillate back and forth in space, so as to remain in contact with the other while also maintaining a tendency to move away from the initial position. In other words, interaction between the agents transforms their motor subsystems, permitting them to jointly generate more complex patterns of behaviour than would be possible for either in isolation.

To be successful the agents need to behave differently depending on whether their initial encounter resulted in leftward or rightward coordination. As we saw, this history-dependent capacity is based on the fact that the neural network can enter into two distinct modes of operation, depending on the chosen direction. In this sense the model helps us to conceive of a possible basis of intercorporeal body memory even in the absence of neuroplasticity: an individual's interaction with others might recruit different loops of neural activity that correspond to distinct histories of social interaction.

But is this dynamical basis of body memory internal to an agent? This question can be addressed in the model by preventing mutual coordination, for example by replacing the responsive behaviour of one agent with a playback of its recorded movements. Under this condition the responsive agent's history-dependent distinct mode of neural activity becomes unstable and collapses into the fixed-point attractor of the isolated neural network. Consequently, the agent ceases to be capable of flexibly coordinating with the other's movements and eventually drifts away. Importantly, this breakdown of interaction is not only caused by the fact that playback movement does not afford mutual coordination. Rather, the core problem is that the agent's very capacity for flexible interaction was based on maintaining a shared history of coordination. The model therefore suggests that dyadic body memory can have a dyadic basis: during their interaction each agent acquires the capacity to flexibly coordinate their own movement with that of the other agent, and this capacity is in turn based on their shared history of mutual coordination.

4. Discussion

Based on these three case studies we will now examine two questions.

4.1 Can these insights be generalised to explicit recollection?

It might be responded that the basis of body memory was an easy target for a dynamical, enactive approach, but that more representation-hungry forms of remembering, such as episodic and autobiographical recollection, would require returning to the standard framework of internal memory storage. To respond to this scepticism is not straightforward, but we offer several considerations.

First, there are a growing number of researchers in cognitive science that treat personal memory in the context of embodied practices of remembering, and see it as commonly intertwined with procedural and habitual body memory (Sutton & Williamson, 2014).

Second, the kind of memory studied in case study 1 is similar to episodic memory in that a single, specific past event of a falling object has an effect on the agent's behaviour. This distinguishes its acquisition from the formation of procedural memory, which often involves repeated experiences. Third, we have assumed for simplicity that we are dealing with instances of implicit memory mainly because of convention: the modelled agents cannot report on their past experience. However, while nonlinguistic animals are in a similar situation, it is starting to become more widely accepted that they can still have episodic, or at least episodic-like, memory (Clayton, Salwiczek & Dickinson, 2007). So we might even say that the agent of case study 1 also has episodic-like memory, albeit presumably of short-term duration, but without any need to appeal to the recollection of internal memory contents.

What, then, could be the alternative basis for declarative episodic memory if we are prepared to accept that it is not based on internal mental content? This is currently an active topic of research for enactive theory and requires further work. At this point it seems plausible that only individuals who have narrative capacities, and specifically the capacity to fashion autobiographical narratives about their past, could have declarative episodic memory (Hutto, 2017; Hutto & Myin, 2017). However, if that proposal is on the right track, then it would be just as difficult to model declarative memory as it is to model natural language comprehension, making it perhaps an impossible challenge (Searle, 1980). Future work could try to integrate that enactive approach to declarative memory with an enactive approach to language (Cuffari et al., 2015), which conceives of language in interactive terms and therefore could help to elucidate the relational basis of declarative memory.

4.2 Does the dynamical approach leave room for a role of the subject?

Fuchs acknowledges explicitly the metaphorical link between his account of the phenomenology of body memory and the conceptual apparatus of the natural sciences. In the context of considering the “taboo” zones of obsessives and the avoidance zones of phobics, Fuchs (2012a, p. 93) notes that “In analogy to a physical field, ‘gravitational effects’, invisible ‘curvatures’ of space, or barriers can appear which restrict or prevent spontaneous movements.” What we have done in this article is to take this analogy seriously and to use models to explore it in a more systematic manner. But perhaps there is a danger of tightening this analogy too much? Consider the following phenomenological assessment:

The memory of the body is an impressive refutation of the dualism of pure consciousness and the physical body, for it cannot be attributed to either of them. When I am dancing, the rhythmic movements originate from my body without a need to steer them deliberately — and yet I am living in my movements, I sense them in advance, and I can modulate them according to the rhythm that I feel: I myself am dancing, and not a ghost in a body machine. (Fuchs, 2012b, p. 11)

On the one hand, the models support this phenomenological account of body memory because they demonstrate how dispositions can be acquired via, and continue to be based, on an agent's history of interactions. They also show how an agent's context-sensitive movements can originate spontaneously during an interaction and without the need to

assume the existence of a central controller that steers them deliberately. And yet they go even further than this: they do not leave any role for the subjective aspects of body memory at all. There is no room for an “I” or self to modulate what is happening in these dynamical systems, and neither would there be in the real world, at least as long as nature is conceived of as a kind of classical clockwork universe.

This points to an interesting tension between dynamical and phenomenological approaches that deserves more attention. If we take the dynamical approach as our ultimate guide, such that there is nothing but mere automatic unfolding of deterministic activity, then this suggests that the phenomenology is misguided about the role of the self: although we certainly live through the movements, we are misled to think that we can somehow modulate them. On the other hand, if we take phenomenology as our ultimate guide, then we are forced to say that the metaphor of physical fields is precisely just that, a metaphor, and that one of its key limitations is that, given that it is a metaphor based on *objective* properties, it will in principle fail to capture the *subjective* properties of body memory.

This is not the place to try to dissolve this tension. Nevertheless, by making the dynamical basis of body memory more precise in the way we have done, it might become possible to specify more precisely what are the potential limitations of such a dynamical account. In particular, this approach challenges us to think more clearly about how a conscious subject could potentially make a difference to their unconscious body’s behaviour in a way that goes beyond being a ghost in a machine. A good starting point for this endeavour would be to note that the agents in these models are still rather disembodied: the models abstract away one of the key characteristics of a subject’s biological embodiment, namely their existence as a materially self-producing individual. This precarious mode of existence is arguably why living beings, in contrast to the artificial agents considered here, are not indifferent about how their movements unfold (Froese, 2017). Even so, more philosophical work is still required to show precisely how this capacity of being intentionally directed, for example by being concerned, could become effective for modulating the course of physical behavior. A more relaxed kind of naturalism that lets go of the classical notion of a dynamical universe might be needed in order to accommodate this possibility.

Acknowledgements: T.F. was supported by CONACyT CB-2013-01 project 221341 and by UNAM-DGAPA-PAPIIT project IA104717.

References

- Beer, R. D. (2014) Dynamical analysis of evolved agents: A primer, in Vargas, P., Di Paolo, E. A., Harvey, I. & Husbands, P. (eds.) *The Horizons of Evolutionary Robotics*, pp. 65–76, Cambridge, MA: MIT Press.
- Bongard, J. C. (2013) Evolutionary robotics, *Communications of the ACM*, 56, pp. 74–83.
- Brooks, R. A. (1991) Intelligence without representation, *Artificial Intelligence*, 47, pp. 139–160.
- Clark, A. & Thornton, C. (1997) Trading spaces: Computation, representation, and the limits of uninformed learning, *Behavioral and Brain Sciences*, 20, pp. 57–90.
- Clayton, N. S., Salwiczek, L. H. & Dickinson, A. (2007) Episodic memory, *Current Biology*, 17, R189–R191.
- Di Paolo, E. A., Noble, J. & Bullock, S. (2000) Simulation models as opaque thought experiments, in Bedau, M. A., McCaskill, J. S., Packard, N. H. & Rasmussen, S. (eds.) *Artificial Life VII: Proceedings of the Seventh International Conference on Artificial Life*, pp. 497–506, Cambridge, MA: MIT Press.

- Froese, T. (2017) Life is precious because it is precarious: Individuality, mortality, and the problem of meaning, in Dodig-Crnkovic, G. & Giovagnoli, R. (eds.) *Representation and Reality in Humans, Other Living Organisms and Intelligent Machines*, pp. 33–50, Cham: Springer.
- Froese, T. (in press) Searching for the conditions of genuine intersubjectivity: From agent-based models to perceptual crossing experiments in Newen, A., De Bruin, L. & Gallagher, S. (eds.) *The Oxford Handbook of 4E Cognition*, Oxford, UK: Oxford University Press.
- Froese, T. & Di Paolo, E. A. (2008) Stability of coordination requires mutuality of interaction in a model of embodied agents, in Asada, M., Hallam, J. C. T., Meyer, J.-A. & Tani, J. (eds.) *From Animals to Animats 10: 10th International Conference on Simulation of Adaptive Behavior, SAB 2008*, pp. 52–61, Berlin: Springer.
- Froese, T. & Fuchs, T. (2012) The extended body: A case study in the neurophenomenology of social interaction, *Phenomenology and the Cognitive Sciences*, 11, pp. 205–235.
- Froese, T. & Gallagher, S. (2010) Phenomenology and artificial life: Toward a technological supplementation of phenomenological methodology, *Husserl Studies*, 26, pp. 83–106.
- Froese, T., Iizuka, H. & Ikegami, T. (2013) From synthetic modeling of social interaction to dynamic theories of brain-body-environment-body-brain systems, *Behavioral and Brain Sciences*, 36, pp. 420–421.
- Fuchs, T. (2012a) Body memory and the unconscious, in Lohmar, D. & Brudzińska, J. (eds.) *Founding Psychoanalysis Phenomenologically: Phenomenological Theory of Subjectivity and the Psychoanalytic Experience*, pp. 69–82, Dordrecht: Springer.
- Fuchs, T. (2012b) The phenomenology of body memory, in Koch, S. C., Fuchs, T., Summa, M. & Müller, C. (eds.) *Body Memory, Metaphor and Movement*, pp. 9–22, Amsterdam: John Benjamins.
- Fuchs, T. (2017) Collective body memories, in Durt, C., Fuchs, T. & Tewes, C. (eds.) *Embodiment, Enaction, and Culture: Investigating the Constitution of the Shared World*, pp. 333–352, Cambridge, MA: MIT Press.
- Harvey, I., Di Paolo, E. A., Wood, R., Quinn, M. & Tuci, E. A. (2005) Evolutionary robotics: A new scientific tool for studying cognition, *Artificial Life*, 11, pp. 79–98.
- Hutto, D. D. (2016) Remembering without stored contents: A philosophical reflection on memory, in Groes, S. (ed.) *Memory in the Twenty-First Century: New Critical Perspectives from the Arts, Humanities, and Sciences*, pp. 229–236, Basingstoke, UK: Palgrave Macmillan.
- Hutto, D. D. (2017) Memory and narrativity, in Bernecker, S. & Michaelian, K. (eds.) *The Handbook of Philosophy of Memory*, pp. 192–204, Oxon, UK: Routledge.
- Hutto, D. D. & Myin, E. (2017) *Evolving Enactivism: Basic Minds Meet Content*, Cambridge, MA, MIT Press.
- Hutto, D. D. & Peeters, A. (in press) The roots of remembering: Radically enactive recollection, in Michaelian, K., Debus, D. & Perrin, D. (eds.) *New Directions in Philosophy of Memory*, Oxon, UK: Routledge.
- Iizuka, H. & Di Paolo, E. A. (2007) Minimal agency detection of embodied agents, in Almeida e Costa, F., Rocha, L. M., Costa, E., Harvey, I. & Coutinho, A. (eds.) *Advances in Artificial Life: 9th European Conference, ECAL 2007*, pp. 485–494, Berlin: Springer.
- Izquierdo, E. (2008) *The dynamics of learning behaviour: A situated, embodied, and dynamical systems approach*, unpublished PhD thesis, University of Sussex.
- Izquierdo, E. J. & Beer, R. D. (2016) The whole worm: Brain-body-environment models of *C. elegans*, *Current Opinion in Neurobiology*, 40, pp. 23–30.
- Izquierdo, E., Harvey, I. & Beer, R. D. (2008) Associative learning on a continuum in evolved dynamical neural networks, *Adaptive Behavior*, 16, pp. 361–384.
- Izquierdo-Torres, E. & Di Paolo, E. A. (2005) Is an embodied system ever purely reactive?, in Capcarrere, M. S., Freitas, A. A., Bentley, P. J., Johnson, C. G. & Timmis, J. (eds.) *Advances in Artificial Life: 8th European Conference, ECAL 2005*, pp. 252–261, Berlin: Springer.
- Izquierdo-Torres, E. & Harvey, I. (2006) Learning on a continuum in evolved dynamical node networks, in Rocha, L. M., Yaeger, L. S., Bedau, M. A., Floreano, D., Goldstone, R. L. & Vespignani, A. (eds.) *Artificial Life X: Proceedings of the Tenth International Conference on the Simulation and Synthesis of Living Systems*, pp. 507–512, Cambridge, MA: MIT Press.
- Loader, P. (2013) Is my memory an extended notebook?, *Review of Philosophy and Psychology*, 4, pp. 167–184.
- Merleau-Ponty, M. (1960/1964) The philosopher and his shadow, in Merleau-Ponty, M., *Signs*, pp. 159–181. Evanston, IL: Northwestern University Press.

- Merleau-Ponty, M. (1964/1968) *The Visible and the Invisible*, Evanston, IL: Northwestern University Press.
- Moran, D. (2017) Intercorporeality and intersubjectivity: A phenomenological exploration of embodiment, in Durt, C., Fuchs, T. & Tewes, C. (eds.) *Embodiment, Enaction, and Culture: Investigating the Constitution of the Shared World*, pp. 25–46, Cambridge, MA: MIT Press.
- Nolfi, S., Bongard, J. C., Husbands, P. & Floreano, D. (2016) Evolutionary robotics, in Siciliano, B. & Khatib, O. (eds.) *Springer Handbook of Robotics*, pp. 2035–2068, Berlin, Heidelberg: Springer.
- Phillips, J. (2017) Merleau-Ponty's nonverbal unconscious, in Legrand, D. & Trigg, D. (eds.) *Unconsciousness Between Phenomenology and Psychoanalysis*, pp. 75–92, Cham: Springer International.
- Searle, J. R. (1980) Minds, brains, and programs, *Behavioral and Brain Sciences*, 3, pp. 417–424.
- Summa, M., Koch, S. C., Fuchs, T. & Müller, C. (2012) Body memory: An integration, in Koch, S. C., Fuchs, T., Summa, M. & Müller, C. (eds.) *Body Memory, Metaphor and Movement*, pp. 471–444, Amsterdam: John Benjamins.
- Sutton, J. & Williamson, K. (2014) Embodied remembering, in Shapiro, L. (ed.) *The Routledge Handbook of Embodied Cognition*, pp. 315–325, Oxon, UK: Routledge.
- Torrance, S. & Froese, T. (2011) An inter-enactive approach to agency: Participatory sense-making, dynamics, and sociality, *Humana.Mente*, 15, pp. 21–53.
- Vargas, P., Di Paolo, E. A., Harvey, I. & Husbands, P. (eds.) (2014) *The Horizons of Evolutionary Robotics*, Cambridge, MA: MIT Press.
- Williams, P. L., Beer, R. D. & Gasser, M. (2008) An embodied dynamical approach to relational categorization, in Love, B. C., McRae, K. & Sloutsky, V. M. (eds.) *Proceedings of the 30th Annual Conference of the Cognitive Science Society*, pp. 223–228, Austin, TX: Cognitive Science Society.
- Ziemke, T. & Thieme, M. (2002) Neuromodulation of reactive sensorimotor mappings as a short-term memory mechanism in delayed response task, *Adaptive Behavior*, 10, pp. 185–199.