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Using Human–Computer Interfaces to Investigate 'Mind-As-It-Could-Be' from the First-Person Perspective

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Abstract There is a growing community of researchers who are interested in establishing a science of the experiential or 'lived' aspects of the human mind. This shift from *cognitive* science to *consciousness* science presents a profound challenge to synthetic approaches. To be sure, symbolic artificial intelligence constituted the original foundation of cognitive science; subsequent progress in robotics has helped to pioneer a new understanding of the mind as essentially embodied, situated, and dynamical, while artificial life has informed the concept of biological self-organization. However, with regard to the development of a science of the experienced mind, the relevance of these synthetic approaches still remains uncertain. We propose to address the challenge of first-person experience by designing new human–computer interfaces, which aim to artificially mediate a participant's sensorimotor loop such that novel kinds of experience can emerge for the user. The advantage of this synthetic approach is that computer interface technology enables us to systematically vary the ways in which participants experience the world and thereby allows us to systematically investigate 'mind-as-it-could-be' from the first-person perspective. We illustrate the basic principles of this method by drawing on examples from our research in sensory substitution, virtual reality, and interactive installation.

Keywords Consciousness · Enaction · Situatedness · Embodiment · Human–computer interface · Technology · Artificial life

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Introduction

The interdisciplinary field of cognitive science has undergone a number of conceptual and methodological transitions since its official beginnings in the early 1970s [2]. To put it very briefly, cognition was first conceived as symbolic computation, then as subsymbolic computation, and then as embodied, situated, and dynamical [3]. Most recently, there has been growing interest in conceiving of mind as rooted in the phenomenon of life, especially as proposed by the 'enactive' approach to cognitive science [4–6].[1] One particularly exciting aspect of this latest development is that life can provide a natural bridge over the mind–body gap [11–13]. In brief, the idea is that our body can be investigated as a special kind of physical object, namely as a living body, and yet at the same time our body is also an essential part of how we subjectively experience ourselves in the world, namely as a lived body. In other words, the enactive notion of the embodied mind goes further than other embodied approaches to cognitive science by claiming that the mind is embodied as a *living*

[1] We are aware that all of these major stages in the history of cognitive science have various precursors in the history of the science of life and mind. In the interest of brevity we do not enter into a more comprehensive historical discussion here (but see, e.g., [3, 7–10]).

(i.e., biological) and *lived* (i.e., phenomenological) body. The hope is that in this way the insurmountable mind–body problem can be transformed into a more tractable body–body problem [11]. One outstanding challenge is to turn this enactive theory of mind into a productive experimental research paradigm, and this paper outlines one possible method that is based on a synthetic approach.

The Enactive Paradigm: Bio-phenomenology as Cognitive Science

The theoretical foundation of the enactive approach is defined by a radical life–mind continuity thesis, which holds that living processes and mental processes share the same kind of organizational principles and are existentially unified as two aspects of one living being [14–17]. Note that life–mind continuity has a double methodological implication for cognitive science: on this view, the study of mind becomes inseparable from the study of organismic existence and from the study of conscious experience [6]. However, given the still predominant focus on cognitive computation in cognitive science, neither of these topics (living and lived phenomena) has received much attention by the scientific mainstream. This means that fundamental theoretical and methodological issues remain to be addressed. In what follows, we mainly focus on the latter. Because the authors of this article have a background in synthetic approaches to cognitive science, we are interested in evaluating the appropriateness of these approaches.

So far, it has remained unclear to what extent insights derived from synthetic approaches can support the shift of focus from cognitive computation of the traditional cognitive science to an investigation of bio-phenomenology as required by enactive cognitive science [18]. At least in the case of previous shifts in cognitive science, the new movements have always been strongly reinforced, if not even initiated, by developments in fields like artificial intelligence, robotics, and artificial life. For instance, regarding the ongoing development of embodied approaches to cognitive science, we now have a better understanding of the importance of sensorimotor dynamics for perception and cognition, and of the way in which sensorimotor coordination enables an embodied agent to self-structure its perceptual affordances (Fig. 1). The growing acceptance of the role of sensorimotor situatedness and embodiment in cognitive science is, to a large extent, based on work in robotics (e.g., [19–23]).

Similarly, research in artificial life has been refining our understanding of the complexity of life in a way beneficial for cognitive science [24]. Artificial life has been especially useful for formalizing the biological organization of the living from the perspective of the enactive approach [25–29]. Indeed, various aspects of the life–mind continuity thesis have been a central topic of interest in artificial life since the beginning, especially the idea that life and mind share a common set of organizational principles [9, 30, 31]. The hypothesis that similar systemic concepts are applicable to life, mind, and sociality lies at the core of the paradigm of enaction [4, 6]. Finally, it should be mentioned that the life–mind continuity thesis has also played a role in the development of new approaches to embodied robotics, which pay closer attention to the organization of living processes [32–35].

However, despite these interdisciplinary advances, it is still unclear how such synthetic approaches can deal with the most radical aspect of the enactive approach, namely the turn toward the experiential aspects of the mind. In contrast to previous paradigm shifts in cognitive science, where breakthrough innovations in the artificial sciences were able to lead the way toward a new framework of scientific understanding, the inspiration for the experiential turn of the enactive approach has come from outside of cognitive science or engineering. One strong influence is the philosophical tradition of first-person phenomenology, coupled with methods drawn from various types of mind–body practice [6, 17, 36]. The general focus is on how phenomena are experienced or 'lived' from the first-person perspective. Thus, if the artificial sciences want to productively engage with this development in cognitive science, they are confronted with a fundamental challenge. It has been well known for a long time that there is a problematic relationship between consciousness and computers [37–41]. However, at least the artificial sciences are not alone in this dilemma. Even the science of consciousness is only slowly coming to terms with the problem of how to

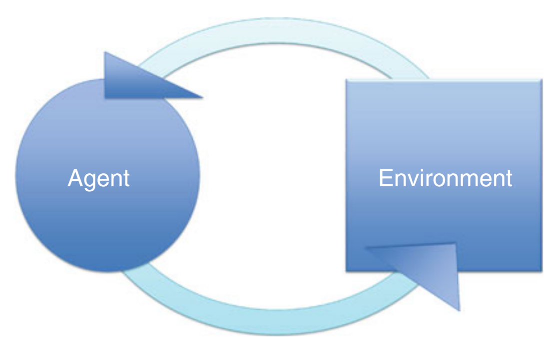

Fig. 1 Diagram of an embodied agent situated in a sensorimotor loop. Following the principles of symbolic AI, cognitive science has traditionally focused on processes of cognitive computation that follow a linear sequence of sensation, representation, cognition, and action. However, more recent synthetic approaches to cognitive science, such as situated robotics and artificial life, have made a substantial contribution to our understanding of the importance of sensorimotor coordination for perception and action. The basic idea is that sensory processing and effector movement cannot be understood in isolation from each other, because they co-determine each other in a continuous manner. This loop enables the agent to structure its sensory flows by means of its bodily activity

best investigate experience as it is lived from the first-person perspective [42, 43].

Moreover, while the artificial sciences are faced by a profound challenge, they are not completely irrelevant for the enactive experiential turn. For instance, they can offer technological supplementation of traditional phenomenological methodology by helping researchers to explore some of the potential structures and dynamics of life and mind [44]. In this manner, artificial systems can serve as an external tool to aid our imaginative variation in the space of possible mental structures [45], but these models are limited to the formal or dynamical aspects of the mind only. Some proponents of machine consciousness may respond that a first-person perspective may eventually be artificially implemented in an embodied robot [46], but in practice, this does not seem feasible for a science of consciousness. There are currently no sufficiently convincing candidate systems, and it is not clear at what point we can expect better human-like performance. More importantly, it may not even be possible to create a conscious computerized robot in principle. Proponents of the enactive approach, for example, emphasize the importance of the principles inherent in messy biological embodiment for consciousness [47, 48]. And even if there were some conscious robots in the distant future, this does not help us in improving the science of consciousness in the present. We simply need a more pragmatic synthetic approach.

The First-Person Perspective: What is it Like to See with your Abdomen?

One of the main problems faced by the synthetic approaches to consciousness science is that the qualities of first-person experience cannot be fully captured by a functional model of that experience. This is of course Chalmers' [39] 'hard problem' of consciousness. A complete understanding of an experiential phenomenon therefore requires us observers to live through it by ourselves. Only thereby can we get acquainted with the phenomenon as it appears from the first-person perspective. In order to better illustrate this irreducibility of the lived first-person perspective, let us consider a prominent debate in cognitive science related to the enactive or sensorimotor account of visual perception [17, 49, 50]. Briefly, this account holds that the experiential quality of the visual modality is constituted by the subject's skillful know-how of the relevant sensorimotor contingencies. In other words, perceptual experience is constituted by a set of skills that enable the goal-directed exploitation of sensorimotor regularities. Accordingly, the deployment of these skills through other means than the eyes should therefore also result in visual experience. But how could this hypothesis about the constitution of visual consciousness be verified?

Proponents of the enactive and sensorimotor accounts are fond of citing Bach-y-Rita's [51] experiments with the tactile-visual sensory substitution system (TVSS) in support of their claims. The TVSS is a human–computer interface that continuously translates the output of a video camera onto an array of tactile stimulators strapped to the user's body, for instance on the abdomen. Under these conditions, some of the blind and blindfolded participants, who had been trained in using the hand-held camera to successfully navigate their environment, spontaneously reported being able to 'see' objects in front of them in external space. However, despite the behavioral successes and spontaneous verbal reports, it is still not clear exactly what the experience of using TVSS is actually like. Resolving this issue is important in order to decide whether the exercise of sensorimotor contingencies is indeed important for perceptual experience. Accordingly, we can ask whether the skillful use of TVSS enables the same perceptual experience as vision or whether it is at least vision-like to some extent [50, 52]. Or does the abdominal interface dominate the quality of the experience such that it becomes a variation of touch or touch-based inference [53, 54]? Or does the TVSS experience perhaps constitute an entirely novel perceptual modality based on the specific kind of sensorimotor profile enabled by the device [55, 56]? We are sympathetic with this last option, but there is currently no way to resolve this ongoing debate. It has been over 40 years since Bach-y-Rita unveiled the TVSS, but there has not yet been a single attempt to make a systematic study of the first-person experience of skilled users (for a brief personal account, see [57]), and so the debate about the first-person quality of using this device will remain highly speculative.

Given the lack of first-person insight into the experience of using TVSS, we are simply in no position to determine which of the competing explanations of the TVSS experience is most appropriate. Moreover, the creation of a synthetic model of the sensorimotor dynamics involved in the use of TVSS will not help, either. As Froese and Spiers [58] have pointed out, these questions about 'what it is like' [59] to use the TVSS cannot be answered with any certainty without oneself actually having tried out the device and lived through the experience of its usage from the first-person perspective. Or, at the very least, we need to elicit more detailed verbal reports from the participants who have had first-person access to the experiences in question, for example through specialized interview methods (e.g., [60]). The science of consciousness is only recently beginning to confront such methodological challenges in a more systematic manner [42, 43].

Toward a New Synthetic Approach

We have argued that the artificial sciences can tell us little about what it is actually like for someone to experience a particular phenomenon from the first-person perspective. This should not be surprising given the well-known debate

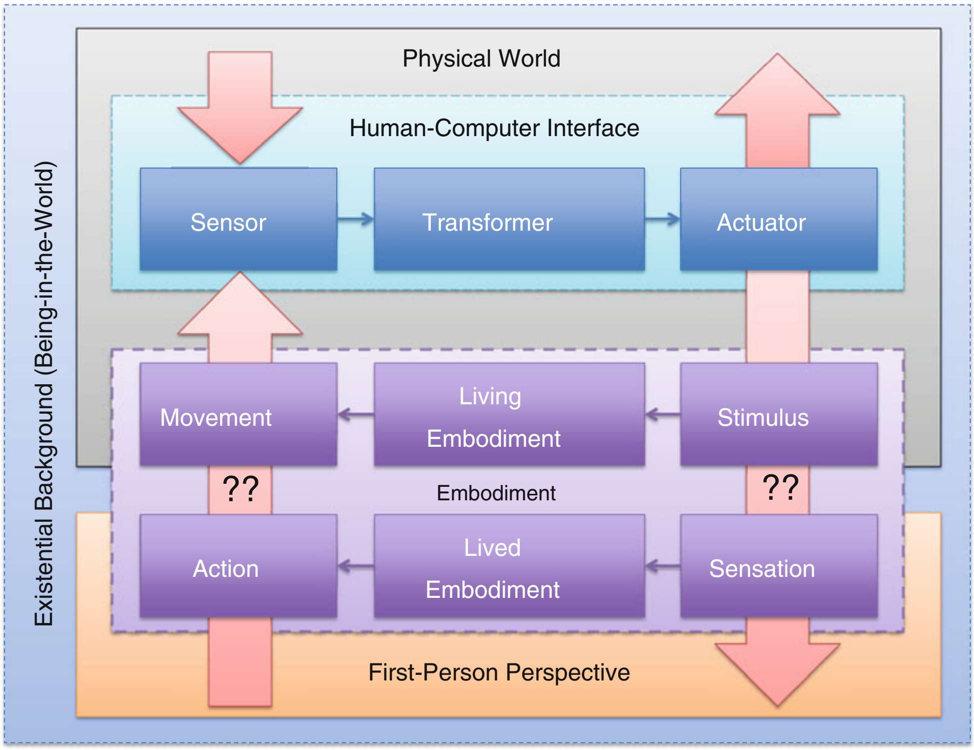

Fig. 2 Schematic illustration of the enactive theory that informs our proposal of using human–computer interfaces to study 'mind-as-it-could-be' from the first-person perspective. The enactive approach attempts to address the explanatory gap of the traditional mind–body problem (represented by *orange* and *gray frames*) by founding its framework on a notion of embodiment that incorporates both the biological living body and phenomenological lived body. Accordingly, a participant's body (*purple frame*) is a part of the physical world and is also a part of their experience from the first-person perspective. The relationships between these two aspects of embodiment are not yet well understood (indicated by *question marks*). However, we can turn this open question into a scientific research program by manipulating the way in which we are embodied and by checking what kind of experiential effects are caused by these changes. A synthetic approach has the advantage of enabling us to create novel human–computer interfaces that systematically mediate the user's sensorimotor dynamics and thereby systematically modulate the user's experience (Color figure online)

about the explanatory gap between theoretical knowledge and experiential insight [59, 61]. Thus, while the synthetic approaches can be used as a technological aid to study how the dynamics of brain, body and world give rise to structural constraints, by itself this research is largely silent about their first-person experiential quality. In order to understand the relationship between dynamics and experience, it is necessary for a human subject to consult their lived experience under appropriate conditions. At least in this respect, therefore, the traditional role of synthetic approaches for pioneering new scientific concepts will be sidelined in the science of consciousness, and an increased focus on actual human subjects will have to necessarily take its place [18].[2]

[2] The same is true of our biological understanding of life and mind. For instance, whereas cognitive science was originally more influenced by abstract computational models than by the results of actual neuroscience, nowadays neuroscience is clearly a much more prestigious area of research. Similarly, the biological foundations of the enactive approach started out as abstract organizational principles, but they are now being revised according to more realistic constraints [10]. Varela [62] referred to this general trend in cognitive science as a 're-enchantment of the concrete'.

Nevertheless, we propose that this development in the history of cognitive science also presents a new opportunity for the artificial sciences. Simply put, if we want to know what kind of experiential qualities are entailed by a specific kind of sensorimotor loop, then all we need to do is to let a human observer enact that sensorimotor loop. More specifically, we want to suggest that the lessons of artificial life and situated robotics can be creatively adapted for the design of human–computer interfaces that transform our living and lived embodiment. An overview of this approach is shown in Fig. 2.

The basic idea is that since the mind is embodied, all we have to do is modify the ways in which the mind is embodied, and the mind will then be modified accordingly. There are many ways of modifying human embodiment. The use of tools and technological interfaces has the advantage of being non-invasive and relatively non-intrusive (e.g., they can be put down at will). And we can build on a tradition of phenomenological research of tool-use, starting with Husserl's analysis of writing, Heidegger's hammer, Merleau-Ponty's blind man's cane, and continuing in recent work [63–65].

This human-centered synthetic approach thereby allows us to address questions related to mapping out additional phenomenological terrain. For example, we could design new sensor and actuator systems much like we would have designed them in the case of robots, but in this case they are supposed to be used by human participants rather than by artificial 'agents'. More generally, we can envision a variety of novel approaches to human–computer interface design [66–68]. In fact, a lot of highly relevant research can already be found in the fields of haptics, enactive and tangible interfaces, prosthetic and assistive technology, virtual and augmented reality systems, the computer gaming industry, and so forth. Although many of these technologies have been developed for specific practical goals rather than for basic scientific research, it is desirable that in the future there will be a much closer mutually informing relationship between cognitive science and these kinds of synthetic approaches. What is of particular interest in the current context is that the skillful use of these interfaces can give rise to new perceptual modalities and augmented sense-making [56]. Although it has been suggested that all technical artifacts are 'enactive' in this sense [68], we follow Froese et al. [69] in reserving the term 'enactive interface' for those devices that facilitate the enaction of new modes of experiences rather than refining existing ones. Although the distinction is not an absolute one, the former type of artifact is more relevant for the new research methodology we are proposing. For example, this allows us to differentiate between the effects of using spectacles, which only improve one's existing eyesight, and the effects of using TVSS, which provides the user with a potentially novel kind of perception of the environment involving abdominal stimulation. In general, enactive interfaces can be used as scientific tools to systematically investigate the phenomenological 'mind-as-it-could-be' from the first-person perspective, thereby giving rise to a method we will refer to as "artificial embodiment" [1]. In what follows, we first describe this synthetic approach in more detail, and then we present some illustrative case studies drawn from our own research in sensory substitution, virtual reality, and interactive installations.

Methods

Artificial Life

The method of artificial embodiment,[3] more specifically of artificially modulating human embodiment, is structurally similar to the one already employed by some existing synthetic approaches, especially by the field of artificial life, except that in this case it is our human embodiment in the world which is systematically manipulated by means of artificial systems. In order to support the idea that this kind of synthetic approach is a logical extension of artificial life, it is important to make their respective goals and methods explicit. In the case of the field of artificial life, we can quote Langton, one of the field's founders, who describes its mission as follows:

> "By extending the horizons of empirical research in biology beyond the territory currently circumscribed by life-as-we-know-it, the study of artificial life gives us access to the domain of life-as-it-could-be, and it is within this vastly larger domain that we must ground general theories of biology and in which we will discover practical and useful applications of biology in our engineering endeavors."[4]

Another way of putting this is to say that the method of artificial life consists of two essential aspects [70]:

(1) it is *synthetic*—i.e., the phenomena to be investigated must be brought into existence by artificially creating the conditions for their emergence and
(2) it is *analytic*—i.e., these phenomena, once they have emerged, are explanatorily opaque and are still in need of further analysis in order to be understood.

It is important to emphasize that both of these aspects are indispensable for doing science: without (1) there is no novel phenomenon that can be the target of an investigation and without (2) there can be no explanation. The synthetic aspect is usually implemented in terms of computer simulations or physical systems, while the analytic aspect is typically realized by means of dynamical systems theory. This methodology of artificial life has been successful in many areas. It has created new proofs of concept, thought experiments, illustrative models, as well as mathematical and technological advances, many of which have been influential in cognitive science [19, 22, 71].

Nevertheless, as we have seen, such artificial life research is limited to the study of the dynamical and physical aspects of living and cognitive systems while excluding experiential considerations. This limitation is not a direct problem for the field of artificial life itself, but it

[3] The name 'artificial embodiment' for this new method is not without ambiguity, especially because it does not explicitly highlight the fact that we are talking about a human-centered synthetic approach. However, for lack of a better phrase, we continue to use it here as a convenient shorthand to denote the method of studying mind-as-it-could-be by artificially varying a person's embodiment via technological means.

[4] C. G. Langton, http://www.biota.org/papers/cglalife.html.

does make the field's relationship with recent developments in cognitive science rather one-sided, especially with respect to the growing interest in phenomenological aspects of life and mind. Since the origins of AI, studies of human experience have been used to justify [72] and to criticize [38] its work, and phenomenology continues to play an informing and critical role [19, 73]. However, as we have argued, it is difficult to conceive the informing relationship between AI and phenomenology the other way around (but see [44, 74] for some attempts).

Artificial Embodiment: Artificial Variation of Lived Embodiment

A human-centered synthetic approach, which is based on the use of enactive interfaces to modulate human embodiment, tries to fill precisely this technology–phenomenology gap by bringing human participants into the domain of the artificial sciences and thereby bringing the first-person perspective along with them. Many of the tools and skills needed for this synthetic approach are already present in any computer science and robotics laboratory. And, of course, there already exists much relevant research regarding human–computer interface design, especially in the field of psychophysics as well as practical areas of engineering and the entertainment industry. These areas have not yet been fully exploited by the science of first-person consciousness, even though user experience is an important part of that research.

One conceptual problem has been the theory of mind characteristic of mainstream cognitive science, which holds that mind is primarily a disembodied symbol processor that is internal to the head. Importantly, it is only once we accept an enactive notion of the embodied and extended mind that we can start to think about using embodiment and tool-use to study consciousness. After rejecting Cartesian mind–body dualism, we begin to realize that first-person experience can be studied in the form of artificial embodiment: because the mind is embodied, we can systematically change the structure of our experience by systematically changing the structure of our embodiment. To be sure, no one would deny that bodily activity and the use of technology change the contents of our experience, because this is trivially true. But the method of artificial embodiment goes further than this in two crucial respects: (1) it accepts that a person's embodiment implicitly structures how they are experiencing those contents in a 'pre-reflective' or 'pre-noetic' manner [75–77], and (2) it accepts that tools can become incorporated into a person's sense of embodiment through their skillful use [78–80]. According to the enactive approach, therefore, skillful tool-use has the potential to modify the pre-reflective structures of our lived experiencing.[5] Paraphrasing Langton's description of the goal of artificial life, we can say that under the label of 'artificial embodiment', we understand a new synthetic methodology that enables us to go beyond the study of *mind-as-we-know-it*, in order to access the vastly larger domain of *mind-as-it-could-be* (Fig. 3).

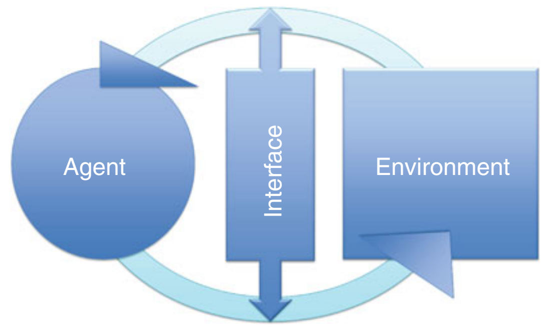

Fig. 3 Structure of our experience depends on the structure of our embodiment, including on our sensorimotor capacities. It is therefore possible to systematically investigate the domain of 'mind-as-it-could-be' by artificially varying human embodiment. There are many possibilities of inducing such variations, but here we focus on the usage-based incorporation of tools created by modern technology, for instance human–computer interfaces and immersive technologies

The aim of this kind of artificial embodiment is to access the technologically enlarged domain of mental phenomena, that is, mind-as-it-could-be, so as to ground general theories of phenomenology and cognitive science and to gain additional technological benefits along the way. Indeed, we envision a mutually beneficial relationship: practical insights gained in the field of human–computer interfaces can support enactive theory in cognitive science, while enactive theory can inform the field of human–computer interfaces. Designing new interfaces in the context of human embodied experience can potentially lead to new technological breakthroughs that change the way in which we relate to the world and each other. Here, we focus primarily on exploring the scientific potential of this technology. The scientific method of artificial embodiment is similar to the one that is already familiar from artificial life [84]:

(1) it is *synthetic*, that is, the phenomena of interest are typically not directly available to human experience, and their conditions of emergence must first be artificially produced by technological means.

[5] The extended mind approach to cognitive science [81] probably entails a similar claim, but there are important differences in emphasis. Whereas the enactive account of lived experience assigns a constitutive role to the interactions between brain, body and (technology) world [79, 82], it seems that the extended mind approach is committed to restricting this account to the interactions within the brain alone [83]. Perhaps future research in artificial embodiment can help to resolve this theoretical difference.

(2) it is *analytic*, that is, the experiential phenomena generated with this technology are in need of detailed description and further analysis in order to become useful for science.

These two aspects of artificial embodiment are not new in themselves. In terms of the synthetic aspect (1), it is possible to draw on much existing research in a diverse set of fields including virtual reality, tool-use, human–computer interfaces, interactive installations, sensory substitution and inversion, and so forth. Much research in psychophysics is also relevant here. We emphasize once more that using technological interfaces to vary user experience has the advantage that we can systematically control and vary the parameters of the interface. In general, all of these fields can be productively linked with theoretical developments in cognitive science, especially regarding embodiment, situatedness, and the extended mind hypothesis [80]. For instance, sensory substitution can be used to study the active constitution of perceptual experience [69, 85, 86], and there has been an increasing interest in using virtual reality as a means of altering consciousness for scientific research [87, 88]. Given the growing consumer demand for human-centered technologies, we expect this to be an increasingly prominent aspect of cognitive science as well. Unfortunately, there is currently much less research available to systematically address the analytic side (2) of artificial embodiment. In what follows, we highlight some potential methods, but these are really only the beginnings of what needs to be a much more systematic effort.

Phenomenology of ‘Mind-As-It-Could-Be’

Informal debriefing interviews have always been a part of psychology, but they typically remain unreported and hardly qualify as a science of phenomenology [42]. Nevertheless, despite lingering behaviorist skepticism against the idea of taking the study of lived experience seriously, acceptance of qualitative research in cognitive science is becoming more popular, especially as it is increasingly driven by concrete practical concerns. How else do you evaluate the success of your new user interface, therapeutic approach, or brain science experiment, to name some prominent examples, except by asking the participants about their experience? As we have seen in the case of TVSS, armchair speculation about those experiences merely serves to reinforce our preconceptions [58]. Accordingly, there is a growing need for methods that allows us to reliably produce phenomenological data in the form of detailed verbal reports [43].

It is beyond the scope of this article to review the different methods that are currently available, but two points are worth emphasizing. First of all, it is essential to follow standard scientific protocol for phenomenological inquiry. Even in cases where it is acknowledged that it is important to take the first-person perspective into account, all too often we find that authors do not include direct quotations of participants’ verbal reports, but merely a summary of what their experience was about. But this confuses raw phenomenological *data* with its subsequent *interpretation* by the experimenter, and the reader is left unable to judge independently whether that interpretation is valid or not. A second, related point is that care must be taken to differentiate as best as possible between asking participants to provide *descriptions* of their experience or *interpretations* of their experience. Both of these approaches can generate useful data in their own right, but they tap into fundamentally different aspects of the mind. For example, if we asked ‘what is it like to use the TVSS?’, a participant may respond by saying, ‘I think it makes me look too much like a cyborg’. Notice that this provides us with the meaning that the participant assigned to the experience, but we have learned nothing about the phenomenological quality of the experience itself, which is underlying the participant’s judgment. Thus, we may then ask, ‘and how did you experience using the TVSS?’, to which we may get a response such as ‘I felt a tickling sensation on my abdomen where the motors make contact with the skin’. This would be an item of phenomenological data, and there are many tricks for shifting the perspective of participants in this manner [60].

We are stressing this difference because of the growing popularity of psychological methods, such as interpretative phenomenological analysis, which claim to investigate ‘lived experience’ and also make use of the phrase ‘what it is like’ [89]. However, they are interested in people’s narrative rather than in ‘what it is like’ for them in the sense of Nagel’s [59] concept of consciousness. Although superficially related, they have little to do with phenomenological method. Artificial embodiment can benefit from such hermeneutic approaches, but they should be clearly distinguished from phenomenologically oriented approaches to consciousness (e.g., [90, 91]).

The enactive approach has championed the idea that phenomenology and cognitive science should establish a mutually informing relationship [17], and this has resulted in a handful of successful case studies [42]. However, as far as we are aware, there has not yet been a systematic application of these phenomenological first- and second-person approaches for investigating the lived experience of the technologically extended and embodied mind. What we are suggesting with the methodology of artificial embodiment is that it would be jointly beneficial for cognitive science, phenomenology, and engineering to work more closely together. Many computer science departments are already involved in conducting some qualitative research, such as usability studies and user experience. Studying the effects of technology on the experience of users is currently primarily driven by practical concerns, but it has the beneficial side effect of advancing the scientific methodology of researching first-person experience at the same time.

Interdisciplinary Circulation

How could this collaboration between interface engineering and the science of consciousness take place in practice? Both the synthetic and analytic sides of artificial embodiment must be integrated. This is essential if the synthetic approach is supposed to systematically produce novel data and hypotheses for the experiential turn in cognitive science. We have already raised some issues regarding phenomenological analysis (for a more detailed discussion of this aspect, see [42, 43]), and in what follows, we focus mainly on the synthetic part of this approach.

The synthetic or constructive approach of artificial embodiment is a variation of the ‘engineering for emergence’ theme that is already familiar from the artificial sciences, but with two crucial differences: (1) the *outcome* of emergence is not focused solely on a new physical ensemble or formal structure, but aims for a novel structuring of lived experience and (2) the *process* of emergence is not only taking place inside the artificial medium, be it a computer, robot, or chemical ‘soup’, but is enacted via the tool-use of a situated and embodied human being. In other words, the idea of ‘engineering for experience’ is to design interfaces that couple with our bodies such that this embodiment–technology interaction spontaneously gives rise to a new structure of lived experience that is of interest to science. The precise nature of this technological mediation can vary: augmentation, substitution, and deprivation are all possibilities [92]. What matters most is that our bodily ways of engaging with the world can be systematically altered by technological means, because this will allow systematic exploration of the embodied ‘mind-as-it-could-be’.

Artificial embodiment has the potential to unify these synthetic approaches by placing them in an explicit relationship with the methodology of artificial life and the experiential turn in cognitive science. The crucial step of moving the idea of artificial embodiment beyond technological wizardry and into a principled scientific research program is to link it to the rest of cognitive science in terms of hypothesis generation and verification. We propose four essential steps:

(1) **Synthesis of interface:** The first step is generally the identification of an interesting way of technologically altering our embodiment, and the synthesis of an appropriate user interface to systematically explore and exploit the kind of variation it enables. For example, the aim could be an exploratory study of a previously unknown type of user experience, or it may be an interference study in order to better assess the nature of an existing phenomenon, or perhaps current explanations of a phenomenon assume conditions of necessity for its appearance that can be manipulated and explored technologically.

(2) **Emergence of experience:** All of these variations are potential sources of phenomenological data for cognitive science. However, while engineers design the interface itself, the experiential effects of its usage cannot be directly pre-specified. There is a theory–experience gap [59, 61]. The participant’s lived experience depends on a variety of largely obscure factors, including the particular history of technologically mediated agent–environment interactions that is enabled by the device synthesized in step (1). Accordingly, this ‘engineering for experience’ faces challenges that are familiar from the notion of ‘engineering for emergence’, but it adds another layer of complexity: the relationship between embodiment and experience.

(3) **Analysis of experience:** The experiential phenomena that emerge in step (2) are essentially ‘opaque’ in that they require further empirical and phenomenological analysis to be properly understood and in order to determine their essential structures and conditions of possibility. Phenomenological data can be generated by using a combination of first- and second-person methods in order to elicit detailed verbal reports of the user experience. Traditional phenomenology typically proceeds by imaginatively varying the phenomena in order to analyze their structure, but the use of technology offers us a more empirically grounded approach, namely by systematically varying the design and parameters of the user interface. This enables us to verify how these technological changes are manifested as changes of user experience.

(4) **Generation of hypotheses:** The phenomenological insights gained in step (3) form the basis for a theoretical evaluation in relation to the study’s original motivation. Did the user experience respond to the variations as expected? If yes, what follow-up questions can we ask on the basis of this confirmation? If not, how and why are the results different? The data inform the process of generating novel hypotheses, which can then become the basis for the design of novel interfaces. The methodological dialectic thus returns to step (1).

These four steps already exist in isolation from each other, and tentative bridges between some of the steps have begun to be formed. But it is the complete *interdisciplinary circulation* between the synthetic, emergent, analytic, and generative aspects that constitute artificial embodiment as an integrated methodology for consciousness science (Fig. 4).

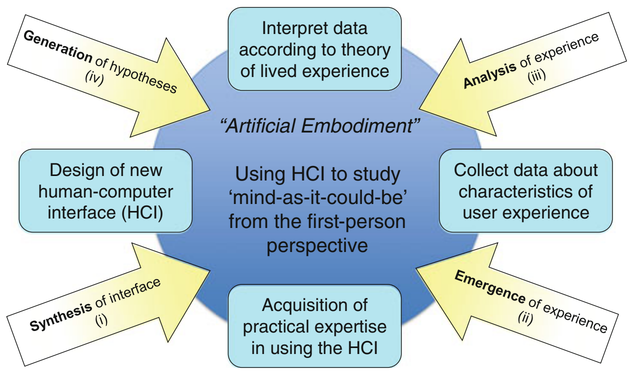

Fig. 4 Illustration of the interdisciplinary circulation required by a synthetic approach to the science of consciousness that is based on artificially varying human embodiment by technological means. There are four essential aspects: *i* synthesis of a new interface in the field of human–computer interface (HCI) engineering; *ii* emergence of a new kind of experience that is lived in the first-person perspective of the interface user; *iii* analysis of that experience from the first-person perspective and perhaps aided by second-person interview methods or other qualitative methods; *iv* generation of new scientific hypotheses based on what has been learned about the relationship between the current interface design, the user's behavior, and the user's experience. These four aspects already exist in various areas of research, but in current practice, they are not related in a mutually informing manner. Our methodological proposal is to explicitly put them into circulation as a synthetic approach to advancing the science of consciousness

Case Studies

After this assessment of the theoretical basis for the method of artificial embodiment, we now turn to some case studies drawn from our own research in this area. We do not claim that these examples succeed in fully realizing the goals of artificial embodiment as it has been outlined above. The aim is rather to illustrate how the methodological passage from artificial life to artificial embodiment can begin to proceed in practice.

Sensory Substitution (I)

A sensory substitution interface is traditionally designed to compensate for the impairment of one of the organic senses by channeling the missing information through another modality. In the case of TVSS, for example, visual information is transformed into tactile information in order to enable blind participants to 'see'. However, according to an enactive or sensorimotor approach to perceptual experience, it is more appropriate to consider the general function of these devices in terms of the possibilities of technologically mediated enaction of a new perceptual modality. In other words, it is a matter of sensorimotor enaction rather than sensory substitution. This generalization of the notion of sensory substitution to an open-ended variety of new experiential domains fits well with the aims of artificial embodiment. A full discussion of this conceptual issue is beyond the scope of this article (but see [55, 56, 69]). For convenience, we continue to refer to these interfaces with the conventional phrase 'sensory substitution', but the reader should keep in mind that we are using it in a much broader sense than it is used traditionally.

The value of using such sensory substitution technology to conduct psychological experiments has long been recognized in cognitive science [86]. In recent examples, sensory substitution interfaces have been used to investigate the experience of depth or *spatiality* [85], the perception of other agents or *alterity* [93], and cross-modal perceptual influences or *synesthesia* [94]. Interestingly, the minimalist design of some of the existing sensory substitution interfaces (e.g., [69, 85, 93]) is reminiscent of the kind of minimalism often advocated in artificial life research [21, 95]. This facilitates the task of synthesis and analysis required for science and is in stark contrast to the current commercial focus on producing the most high-resolution sensory substitution interfaces. This may be thought of one way in which Brooks' famous situated robotics principle that the 'world is its own best model' [23] has been usefully applied in the design of human–computer interfaces: representation is replaced by enaction.

After this brief introduction to sensory substitution technology, we now consider a specific example in which this resemblance to artificial life is clearly visible. Ogai et al. developed an "active tactile system," which is an interface that consists of a small tactile display that is fitted on the tip of a participant's finger and a 3D position sensor that is fitted on the back of the user's hand [96–98]. The position measurements generated by the participant's hand movements are used as inputs for a recurrent neural network (RNN), and the outputs from the RNN are fed back to the participant's finger by means of an actuator based on ionic conducting polymer gel film (ICPF). As a result, the participant feels a tactile sensation that is contingent on their movements and on the dynamics of the RNN. The overall design of the active tactile system is illustrated in Fig. 5, a close-up of the ICPF tactile feedback device is shown in Fig. 6, and the interface's placement on the participant's hand is shown in Fig. 7.

The task of the participants is to optimize the RNN so that the inputs of their hand movements drive the response profile of the ICPF on the tip of their finger such that the tactile feeling of certain textures arises. This training is achieved by means of 'interactive evolutionary computation', an optimization method which is inspired by Dawkin's [100] approach to evolving 'biomorphs' but which has been generalized to other experiences than merely visual esthetics [101]. In this case, two Japanese onomatopoeias, *uneune* and *zarazara*, are used as the goals of optimization. *Uneune* means 'the tactile sensation of

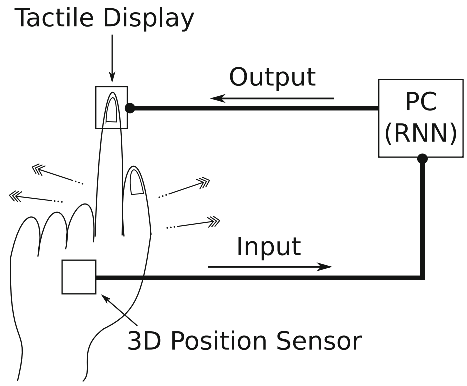

Fig. 5 Illustration of the 'active tactile system' developed by Ogai et al. [97, 99]. The interface makes use of basic artificial life principles to investigate the experience of tactile sensations, especially those that are typically described by onomatopoeias. There is a 3D position sensor located on the back of the participant's hand. The measurements of the hand's movements provide input to a recurrent neural network (RNN) running on the PC. The output of the RNN determines the response of the tactile display attached to the tip of the participant's finger, which is powered by a constant voltage power supply. Interactive evolutionary optimization of the structure of the RNN allows participants to customize the configuration of the active tactile system to match the tactile feeling of different kinds of textures and onomatopoeias

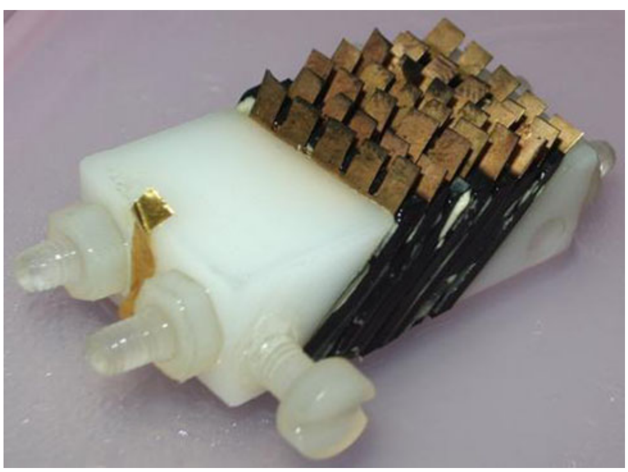

Fig. 6 Close-up picture of the small tactile display used in the active tactile system. It consists of ionic conducting polymer gel film (ICPF) elements [99]. Participants wear this display on the finger cushion of their index finger (see Fig. 7)

winding things', and *zarazara* means 'the tactile sensation of a coarse surface.' Subjects were asked to optimize the RNNs, using interactive evolutionary computation, such that the experience of the ICPF-mediated sensorimotor loop became like the tactile sensation normally referred to by the words *uneune* and *zarazara*. When a participant chose the same RNN configuration 10 times continuously, the optimization of the RNN was regarded as completed.

After the RNN training, each participant was asked to distinguish between the experience of sensations that were

Fig. 7 Picture of the active tactile system as it is being worn by a participant. The 3D position sensor is visible on the back of the hand, and the ICPF-based tactile display is visible on the tip of the index finger [96]

evolved by the participant and those that were evolved by other participants. Interestingly, the experimental results show that it is more difficult for participants to solve this first-person experience discriminatory task in the case of *zarazara* compared to the case of *uneune*. It is therefore possible that the sensorimotor dynamics underlying the sensation of *zarazara* are relatively independent from the participants' personal styles of exploratory movement. Accordingly, Ogai et al. [97] suggest that the experience of *uneune* involves a higher degree of active perception than *zarazara*.

By interlinking engineering, phenomenology, and science, Ogai et al. have, in a nutshell, demonstrated the method of artificial embodiment: the experiment begins with the synthesis of a new interface, which gives rise to a novel perceptual experience, which is then evaluated by the users according to a set of phenomenological criteria, and whose outcome consequently leads to a modification of the interface, and so forth. Once this methodological circle had become stabilized, an experiment was conducted in order to derive a new hypothesis about the sensorimotor constitution of these experiences.

Virtual Reality Substitution

Virtual reality (VR) systems have long been a hot topic of research, and the technology has progressed to a level that VR systems can be used as tools for consciousness science [88]. One of the most studied phenomenological aspects of the user's experience of the VR environment is the feeling of being situated in a world or *presence* [102]. For instance, it has been found that the intensity of presence is strongly dependent on the VR system's responsiveness to the user's bodily actions [103], which supports an enactive approach

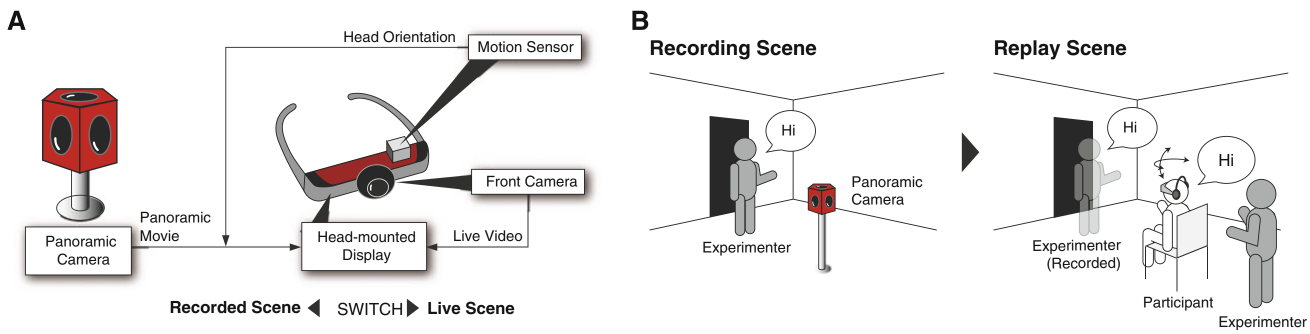

Fig. 8 Illustration of Suzuki et al. "reality substitution platform". **a** The system consists of a panoramic camera capturing whole-directional video (*left*) and a head-mounted display (HMD) with a front camera and a motion sensor (*right*). The scene projected in the HMD can be switched between a live view, which is directly captured through the front camera, and a recorded view, which was pre-recorded with the panoramic camera. The recorded view is cropped in real time according to the head orientation measured by the motion sensor, such that visuomotor experiences in both types of scene are mostly identical. **b** An example of reality substitution enabled by the platform. First, the panoramic camera records the whole scene in the room in advance (*left*). Later, when a participant enters the room wearing the HMD, they see the live view through the front camera. They are asked to sit down on a chair. The panoramic camera was previously positioned in the same location, thereby ensuring that their perspective will match that of the recorded video. Then, without warning, the experimenter switches the video projected in the HMD to the recorded scene. The persistence of consistent visuomotor coupling after the switch assures that the participant continues to experience really being 'here and now' even during the replay scene (*right*). They fail to notice that they are now experiencing a virtual reality

to perceptual experience. Recently, VR systems have also been used to systematically vary one's sense of embodiment, even to the extent of inducing 'out-of-body' experiences [87]. This kind of VR-based research presents us with another example of the interlinking between engineering, phenomenology, and science that is characteristic of the methodology of artificial embodiment.

Despite these advances, there has been a significant constraint in using VR technology for consciousness science in this manner. Participants feel some presence when immersed in using a VR system; however, in most cases, the users still retain awareness of the fact that they are experiencing an artificial world. This lingering awareness of the virtual world's inherent virtuality limits the scientific potential of VR systems, because it requires a suspension of disbelief that is not part of our normal sense of reality. For example, we could ask to what extent intact reality checking plays a role in the constitution of VR-enabled out-of-body experiences. In other words, the feeling of being present in an *artificial* world *as such* may facilitate the enaction of some kinds of experiences, but it may also modify them and perhaps prevent some kinds from arising altogether. So far, it has been impossible to systematically disentangle this confluence of factors.

The traditional approach to designing VR systems that evoke a more convincing experience of being immersed in real reality is based on improving on some objectively measurable aspects of the virtual reality, with the aim of increasing their correspondence with physical reality. For instance, engineers try to perfect the underlying physics model and to increase the resolution of the display while at the same time having to make sure that this additional complexity does not negatively impact the responsiveness of the system. This strategy may make sense from a classical cognitivist theory of mind, which holds that perception is about creating detailed internal world models. But it appears as misguided from the perspective of embodied and situated robotics, which emphasize interaction rather than representation [21, 23]. Similarly, we now have extensive empirical evidence that supports an enactive account of perception, which holds that our sense of experiencing a highly detailed world does not depend on a highly detailed inner model, but is enabled by our practical know-how of regulating sensorimotor dependencies [104].

Suzuki et al. [105] designed a novel type of VR system in order to avoid these problems. Their system is developed specifically for users to have the unquestioned conviction that they are still present in the real world, even when they perceive an artificial world. In order to accomplish this, they take an enactive approach to VR system design: the primary aim is to enable users to engage in smooth sensorimotor interaction, while considerations of resolution are secondary aspects. In fact, they take the opposite approach, namely of *decreasing* the resolution of how the *real* world appears through the head-mounted display system. This allows the experimenters to switch the display feed from the live video view to the virtual reality view, which is based on a previous panoramic recording of the scene, while retaining the same video quality as well as smooth visuomotor coupling (Fig. 8). Even though the visual quality of the display is relatively low compared to normal vision, people strongly believe that they are in the 'here and now' even when they are immersed in the pre-recorded scenes. People cannot tell when they are presented with a virtual scene because, just as in the live view, the visual quality is the same and they can easily turn and see wherever they want. The smooth sensorimotor regulation of the 'reality substitution' effect is achieved by using a panoramic camera to pre-record the participant's environment and to present the appropriately head-oriented section of the panoramic movie on the basis of a head-orientation tracker located inside the head-mounted display. At least under some restricted conditions, especially when view of one's own body is restricted, most participants will fail to distinguish between the artificial and live visuomotor coupling, and their felt presence is therefore of being in normal reality.

Suzuki et al. reality substitution platform nicely illustrates why the research program we are proposing is more appropriately called 'artificial embodiment' rather than 'artificial experience'. Of course, the system that is used to generate the experience by modifying our embodiment is clearly artificial, in the sense of being an artifact. However, the experience, which the user brings forth with their technologically mediated interactions, is not necessarily experienced *as* based on something artificial. In the case of Ogai's active tactile system, the users had a real experience of texture at the tip of their fingers, even though they remained aware of the artificiality of the context in which that experience was generated. The reality substitution approach goes even further by eliminating the experience of artificiality altogether. The lived sense of reality thus becomes another phenomenological aspect that can be systematically varied for research purposes. The system may, for instance, be used to evoke feelings of déjà vu and derealization for experimental study. Importantly, it also raises the tantalizing possibility of extending the method of artificial embodiment to include new variations of our sensorimotor embodiment that would be difficult to engineer and synthesize in physical reality.

Interactive Installation

It could be said that artists have been practicing the method of artificial embodiment all along, because they bring together various technologies and scientific insights in order to generate novel ways of experiencing. More specifically, there has been a long history of using engineering to make interactive installations, and this approach was greatly helped by the computer revolution during the last century. In fact, there has been a close association between interactive art and artificial life, dating back to the early days of cybernetics [106]. But while this art is mainly interested in generating new ways of experiencing, the specific aim of artificial embodiment is to investigate these changes of experience within a scientific research context. That these two goals do not have to be mutually exclusive is nicely demonstrated by the mind time machine (MTM), which was created by Ikegami et al. [107–109].

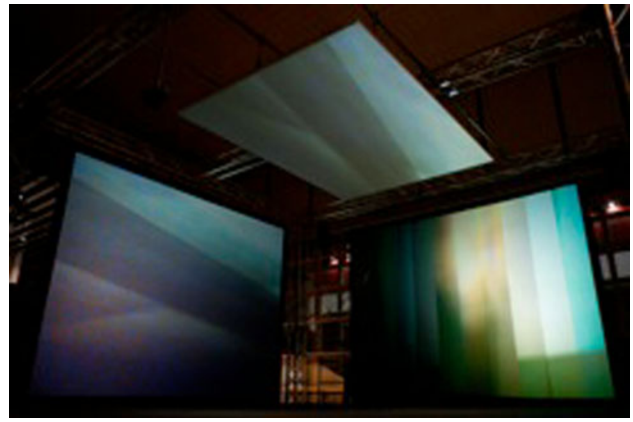

Fig. 9 View of the three screens of the mind time machine (MTM) during a display at the Yamaguchi Center for Arts and Media, Tokyo, in 2010 (photograph by Kenshu Shintsubo). The MTM projects video output onto these screens and then records its own projection with video cameras, thus forming a video feedback loop. People can walk into this large-scale installation and interact with the system by interfering with the video projections. Participants are able to experience the effects their interference has on the dynamics of the video feedback loop

The MTM is an interactive installation based on the principles of artificial life. The system is designed to self-sustain its rich dynamics over long periods of time in an open-ended environment, typically a public exhibition venue. The outputs of the MTM consist of three large screens (right, left, and above on the ceiling), which are displayed as faces of a cubic skeleton 5.4 m in diameter (see Fig. 9).

Fifteen video cameras attached to each pole of the skeletal frame view things happening inside the venue, including its own screens, thereby creating a video feedback loop. The video recordings are decomposed into frames and are subsequently processed by RNNs whose dynamics combine, reverse, and superpose the frames to produce new frame sequences. The system itself is a completely deterministic system, using no random numbers, but it projects different images depending on the inherent instabilities of the neural dynamics that reflect environmental light conditions, movements of people coming to the venue, and the system's stored memory. The central idea is to run the neural dynamics with Hebbian plasticity and optical feedback in order to enable the emergence of autonomous self-organizing phenomena that maintain their complexity over large timescales. It is beyond the scope of this section to go into a detailed analysis of this long-term data (but see [109]). An example of how the screen images change during a short period of time is shown in Fig. 10.

While the MTM was tested extensively in the context of an artistic exhibition, it cannot be neatly categorized as an art project. On the one hand, the MTM can also be conceived as a peculiar example of artificial life research, because it uses the principles from that field and displays adaptive behavior. It also allows us to investigate the necessary conditions for the continuous maintenance of complex behavior in the real world, which remains an open scientific problem. On the other hand, the MTM can also be viewed from the perspective of artificial embodiment because a crucial component of the MTM's operating environment is actual people and the way in which they experience the MTM's screens.

The way in which the interaction between the MTM and visitors affects the visitors' way of experiencing the installation is subtle. Visitors of the MTM can walk into the installation where they interact with its displays through their bodily presence and by casting shadows. Accordingly, their movements appear in the machine's video recordings and, after some internal processing, are projected back out onto the screens. The human participants are thereby immersed within the MTM's sensorimotor loop, just like the MTM is mediating theirs. Crucially, it is the first-person experience of the participants, which plays a role in determining how they will respond to the unfolding interaction process. It has been observed that under certain conditions, the relative coordination between a person's sensorimotor loop and the MTM's sensorimotor loop results in a mutual entrainment between the two: the person–MTM interaction process itself becomes temporarily self-sustaining and tends to prolong the interested presence of the participant. Future research could determine whether these situations are phenomenologically similar to the second-person perspective that is characteristic of normal one-on-one social interactions.

A detailed evaluation of the MTM user experience is of scientific interest in at least two respects. First, it may help to address the difficult methodological question of how to determine whether the system has characteristics of agency or not. The measurement of agency is a long-standing problem in artificial life, and one solution that has not yet received sufficient attention is to evaluate whether human participants are *experiencing* the responses of the system as being informed by an external source of agency or not. The method of artificial embodiment could thus be extended to evaluate the agential status of artificial systems in terms of the social quality of the lived experience of the participants who interact with it. Second, a phenomenological approach to the problem of agency detection is also of great interest to cognitive science. A system like the MTM enables us to investigate the kinds of interaction dynamics that give rise to a sense of presence of another agent (alterity) in a real-world context. Moving beyond fleeting sensations of agency, a challenge would be to show that the conditions underlying this sense of external presence could be maintained over large timescales. However, this raises additional issues of measurement and analysis in the context of massive data flow, which requires the development of new investigative tools. Some of these may have to be situated at a more personal level. For instance, when Ikegami and colleagues kept a daily diary of the MTM's activity, they were able to

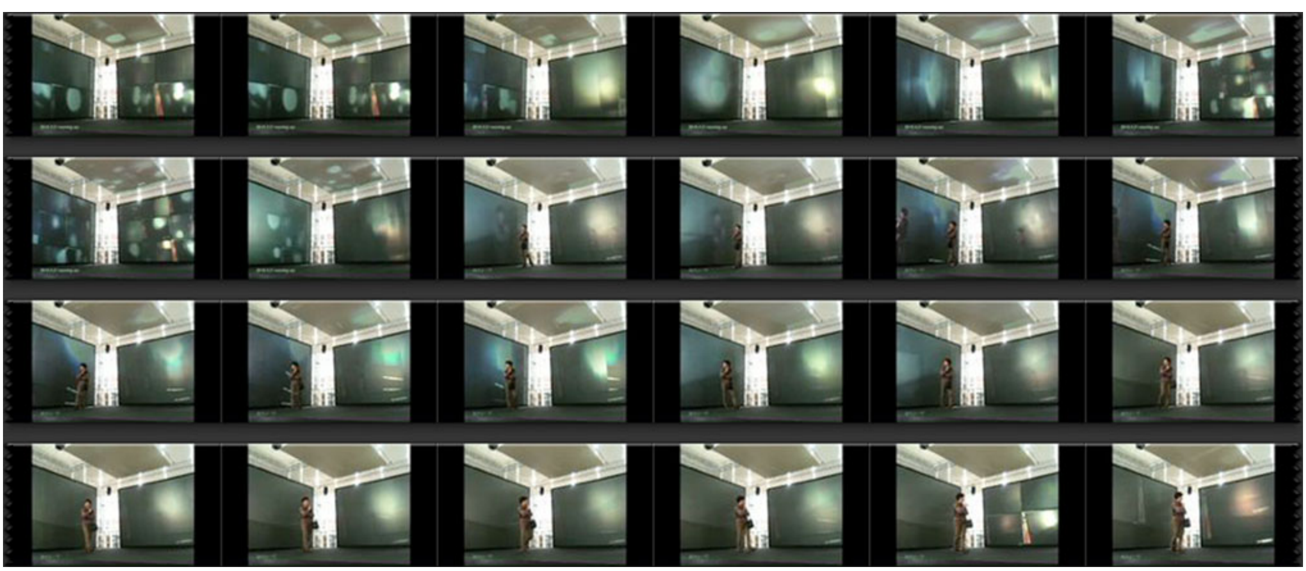

Fig. 10 A series of photographs illustrating how the video projections onto the three screens of the mind time machine (MTM) change over a short period of time. A woman enters the scene and finds that the MTM has reacted by projecting her image onto the screens. For a while, she observes how her image is modified on the left screen. Then, the autonomous dynamics of the MTM take over, and her image disappears. It is replaced by images composed of the MTM's long-term memory. The woman waits for her image to reappear, but eventually she looses interest and turns away. The MTM's potential for interactive behavior coupled with the unpredictability coming from its autonomous dynamics is an attempt to give participants an experience of engaging with an artificial form of agency

correlate long-term changes in its general level of activity with long-term changes in weather conditions [108].

Sensory Substitution (II)

Large-scale artificial systems like the MTM can facilitate the participant's enaction of novel experiences that could not be obtained in other ways. But this kind of synthetic approach to phenomenological variation comes at a scientific price, because other research groups cannot easily replicate the study for verification and further experimentation. Of course, this problem is to some extent unavoidable when the context of artificial embodiment is an art installation, the navigation of a space shuttle, the operation of the Large Hadron Collider, and so forth. But this issue also occurs all too often with scientific experiments based on custom-built devices. Potential for replication is necessary for science in general, and it is especially important when the phenomenon that is to be explained has to be personally experienced. Otherwise, if the reported kind of experience cannot in principle or practice be verified by other researchers from their own first-person perspective, there is a danger of getting caught up in debates that are not properly experientially grounded. Consider, for example, the still unresolved discussion about whether the experience of using the TVSS is a form of vision, somewhat vision-like, touch, touch-based inference, or actually a novel perceptual modality [58]. How can we assess the TVSS experience more systematically? Given that the original TVSS is not available for research purposes, we will probably never know with any certainty what the first-person experience of using it is actually like.

To some extent, the problems of replication are already familiar from artificial life. Even in the case of relatively simple systems, it is often extremely difficult to replicate and verify the results of other researchers, but with complex systems, it quickly becomes impossible. A certain amount of minimalism is therefore indispensible if the systems are supposed to be synthesized by others members of the scientific community for further study. Similar considerations also apply to the synthetic basis of artificial embodiment. Factors to consider include the public availability of the technology, its price, but also human-related factors such as non-intrusive usage, and minimal training times. But the necessity for not only *experimental* but also *experiential* verification puts additional constraints on the analytic methods employed by artificial embodiment. It is impossible to expect all researchers and their experimental participants to become experts at becoming aware and describing their lived experience. Becoming aware is a skill that requires sustained practice and depends upon a personal commitment to undergo a long and difficult process of training [36]. This makes so-called second-person approaches especially attractive, because the participants' process of becoming aware of their user experience can then be facilitated by a skilled interviewer [60]. There still remain some open questions about the calibration of these methods and about the validation of their results [43], but these issues are not specific to artificial embodiment. What is crucial for the science of artificial embodiment is that the realization of the experiments and the application of phenomenological methods depend on the availability of the particular technology in question.

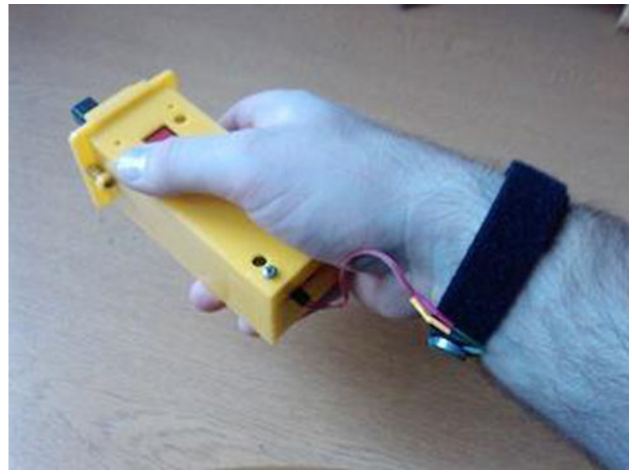

Fig. 11 Example of a recent version of the enactive torch (ET), a minimalist distance-to-touch sensory substitution interface (photograph by Marek McGann). A single channel of distance measures is continuously transformed into variations of vibrational intensity, with closer distances resulting in more intense vibration. This version uses an infrared sensor, which is visible at the top end of the device, and the vibro-tactile motor is strapped to the arm using a Velcro wristband

Froese and Spiers [58] designed a minimalist enactive interface specifically for the purpose of facilitating the study of enactive perception from the first-person perspective. The enactive torch (ET) is a hand-held distance-to-touch sensory substitution interface, which consists of a single, continuous parameter of sensorimotor coupling, namely a distance measure (taken by means of ultrasonic or infrared sensors) that is translated into variations of vibrotactile intensity in the user's hand or arm (see Fig. 11).

Despite the highly impoverished stimulus of one source of continuous vibration, the ET quickly allows visually impaired and blind-folded participants to feel distances by actively scanning the environment with the device. Again we have the idea of replacing representation with enaction, because it is the participants' style of movements that determines the overall spatiotemporal resolution of their perceptual experience. The more a user moves the device, the more they will perceive about the world. By pointing the ET into different directions, participants are able to get a sense of the layout of 3D space around them even though the device itself only provides 1D output. In contrast to the relatively long periods of training that are required by high-resolution sensory substitution interfaces, after a few minutes of practice, many participants spontaneously report that their attention is directed toward things that are perceived in the world, rather than focused on the sensations located at the tactile interface on their arm. A recent study of the phenomenological characteristics of the ET user experience during a maze navigation task has revealed a complex mixture of distal perception, tactile sensations, reflective control, and unspecific feeling [69]. These results further support the notion of artificial embodiment because even minimalist enactive interfaces enable users to vary their experiences through the augmentation of their normal sense-making capabilities. Interestingly, while the use of elongated tools usually leads to characteristic changes in the user's sense of embodiment, such changes in body image were not found in the case of the ET, indicating that distal manipulability is a distinct factor from distal perceivability [110].

The ET therefore provides an intuitive research platform to investigate the interrelated development of bodily skills and perceptual experiences, including the exteriorization of sensory stimuli, changes in embodiment, as well as cross-modal influences.[6] Easy programmability of the response profile, onboard data recording capabilities of motor and sensor activity, as well as accelerometer-based measures of participants' arm movements provide a convenient basis to study the effects of sensorimotor dynamics. In addition, recent versions of the ET have become more modularized such that the experiential characteristics of other sensor and motor configurations can be systematically explored [69]. We note also that the design of the ET has been made publicly available and is licensed under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported (CC BY-NC-SA 3.0) license. This should help to mitigate some of the worries regarding the difficulties of scientific replication of results that have been obtained by means of artificial embodiment.

Concluding Remarks

We have proposed a new research method of 'artificial embodiment', which draws on the theoretical insights and the practical methods developed in the field of artificial life. The main idea is to engineer interfaces that become incorporated into the embodiment of human participants through their skillful usage. These variations of embodiment thereby enable us to systematically investigate the general principles of the technologically mediated embodied mind-as-it-could-be. We have presented some case studies drawn from our own research, which illustrate the potential of this human-centered synthetic approach. However, these are only some exploratory beginnings of what needs to become a long-term research project. In general, more effort must be made to connect the resulting technological devices and the new experiences they facilitate with the theoretical, experimental, and phenomenological concerns of cognitive science.

We have introduced this human-centered synthetic method by drawing on the philosophy of the enactive approach, so it is fitting to conclude with some philosophical remarks. As evidenced by this special issue, most synthetic approaches to 'computational intelligence, creativity, and autonomy' are motivated by the prospect of engineering these desirable human properties into robotic systems. We can make sense of the continuing force of this motivation from the lingering metaphysics of Cartesian dualism, which still informs much modern thinking about technology. On this view, mind and world are two independent and non-intersecting domains, and technology is strictly confined to the world alone. Starting from this Cartesian mind–technics dualism, the only conceivable possibility of creating a productive mixture between these two human capacities, that is, mind and technology, is by trying to externalize the properties of the mind into some autonomous technology. Hence, there is a widespread fascination with artificial intelligence and living technology, both in science and in engineering. But the goal of engineering truly autonomous systems is actually an impoverished vision of the full potential of technology [64]. For instance, the implementation of genuine human-independent autonomy in an artificial system would limit that system's potential for external control and therefore for usage by humans. Simply put, we do not want our airplanes to be as free as birds.

Luckily, the lingering assumption of a fundamental mind–technics dualism is quickly becoming a thing of the past in both theory and practice. This helps to shift the design stance from a focus on creating independent autonomous systems to facilitating interactive human mediation [69]. In terms of engineering practice, designing for enhanced user experience is becoming a major driving force, especially given that purely functional considerations are becoming less relevant for a post-industrial age. Indeed, entire new markets have been created by human–computer interfaces that are designed in a more human-centered manner. The ubiquity of computer technology is

[6] Interestingly, the potential role of cross-modal influences was only discovered during a second-person interview, where it turned out that the motor sounds of the vibro-tactile interface modulated the appearance of the perceptual space afforded by the device. The discovery of this unforeseen effect, which emerged without having been designed explicitly as a feature, highlights the need for a tight integration between the synthetic and analytic aspects of artificial embodiment in order to capture emergent effects.

ever more subtly changing the way in which we perceive the world and ourselves, and we expect this trend to accelerate. Theories in mainstream cognitive science have been lagging behind these practical developments, but there is a growing acceptance of extended, embodied, embedded, and enactive approaches [5, 80, 81]. This ongoing shift in perspective is fortunate because there is an urgent need for more scientific clarity about the principles of the technological mind. Importantly, the rejection of the traditional mind–technics dualism has exposed a deep vulnerability of the human condition to its own technical environment. If the theory of enaction is on the right track, then using a human–computer interface does not merely provide us with sensory input; it changes the way in which we can experience and engage with the world. This poses an ethical problem: how can positive kinds of technological mediation be identified and promoted, while undesirable consequences are avoided? Accordingly, going beyond the immediate demands of the consumer industry, we need to ensure that cognitive science is in the best possible position to inform the creation of policies regarding the most desirable directions of technological progress.

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