

FOCUS ARTICLE

Robotic interfaces for cognitive psychology and embodiment research: A research roadmap

Philipp Beckerle^{1,2}  | Claudio Castellini³  | Bigna Lenggenhager⁴ ¹Elastic Lightweight Robotics Group, Robotics Research Institute, Technische Universität Dortmund, Dortmund, Germany²Institute for Mechatronic Systems in Mechanical Engineering, Technische Universität Darmstadt, Darmstadt, Germany³Institut of Robotics and Mechatronics, DLR German Aerospace Center, Oberpfaffenhofen, Germany⁴Cognitive Neuropsychology, Department of Psychology, University of Zurich, Zurich, Switzerland**Correspondence**Philipp Beckerle, Elastic Lightweight Robotics Group, Robotics Research Institute, Technische Universität Dortmund, Dortmund, Germany.
Email: philipp.beckerle@tu-dortmund.de**Funding information**

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Advanced human–machine interfaces render robotic devices applicable to study and enhance human cognition. This turns robots into formidable neuroscientific tools to study processes such as the adaptation between a human operator and the operated robotic device and how this adaptation modulates human embodiment and embodied cognition. We analyze bidirectional human–machine interface (bHMI) technologies for transparent information transfer between a human and a robot via efferent and afferent channels. Even if such interfaces have a tremendous positive impact on feedback loops and embodiment, advanced bHMIs face immense technological challenges. We critically discuss existing technical approaches, mainly focusing on haptics, and suggest extensions thereof, which include other aspects of touch. Moreover, we point out other potential constraints such as limited functionality, semi-autonomy, intent-detection, and feedback methods. From this, we develop a research roadmap to guide understanding and development of bidirectional human–machine interfaces that enable robotic experiments to empirically study the human mind and embodiment. We conclude the integration of dexterous control and multisensory feedback to be a promising roadmap towards future robotic interfaces, especially regarding applications in the cognitive sciences.

This article is categorized under:

Computer Science > Robotics

Psychology > Motor Skill and Performance

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KEYWORDS

cognitive science, embodiment, human–machine interfaces, robotics, sensory substitution

1 | INTRODUCTION

Human–machine interfaces (HMIs) are advancing so rapidly that they almost unexpectedly developed into a formidable tool to study the human mind and its underlying neural mechanisms. Recent HMIs provide a unique possibility to study adaptive processes between human beings, robots, and the environment, which is interesting for a variety of theoretical and applied fields; most excitingly may be the study of embodiment and embodied cognition and with it the plasticity of the bodily self (Apps & Tsakiris, 2014; Blanke, 2012). Studying to what extent and under which preconditions humans adapt to a machine might inform us about basic mechanisms of embodiment and embodied cognition, which are typically difficult concepts to study since the human body is “always there” (James, 1890) and cannot easily be experimentally modified (Tsakiris & Haggard, 2005).

At the very core of these advances, we put the concept of *bidirectional HMIs* (bHMIs), that is, systems that are able to close or enhance the sensorimotor feedback loop between human and machine. A bHMI should swiftly, faithfully, transparently channel sensorimotor information via efferent (intent detection) as well as afferent (sensory substitution) pathways. It would hence concurrently be a powerful means for robotic control and a window into human perception, action, and cognition. Yet, bHMIs face great technological challenges, which are closely coupled to the complexity of the human mind. This paper puts forward suggestions on how to design bHMIs while considering the aim to use them to study embodiment and embodied cognition, and describes what we could achieve through these advances. We outline the state of the art, define the fundamental concept of a bHMI, and crystallize technical and human-related key points to be tackled by the community.

2 | BACKGROUND

Recently, the science of interfacing humans and machines has made huge leaps forward, mainly thanks to ever-better (real-time, reliable, dexterous) intent detection and sensory feedback (see Figure 1). Human–robot interaction (HRI) and human–machine interfaces (HMIs) are nowadays enforcing the possibility to use robotic devices to *study and enhance human cognition* next to their traditional use, as recently nicely pointed out by Rognini and Blanke (2016). This trend bears great potential for research in psychology and neurosciences (Kappers & Bergmann Tiest, 2013), as well as for various applied and clinical sciences, and revolves around the concept of *co-adaptation*. With respect to the study of embodiment and embodied cognition, the crucial parameters for certain aspects of embodiment, such as the feeling of ownership or the feeling of agency, might be identified within this process. Typically, related research is currently based on behavioral experiments trying to induce embodiment over a virtual or artificial body part (Botvinick & Cohen, 1998), through the manipulation of multisensory or sensorimotor contingency. As opposed to that, or rather as a companion to it, the robotic approach might overcome the most important limitations and pitfalls of these studies, as it allows better-controlled, for example, more systematic variations of delays, more flexible and longer-term alterations of sensorimotor processes, which is crucial to study adaptation. The latter is especially relevant as altered-embodiment studies typically last only a few minutes due to the manner of the experimental manipulation. Stratton (1899) presents an interesting exception, describing gradual changes in embodiment during longer-term alteration of sensorimotor contingency. It should be noted that most attempts to examine the embodiment of robotic devices have been focused on certain body parts (Romano, Caffa, Hernandez-Arieta, Brugger, & Maravita, 2015; Caspar et al., 2015; Hara, Nabae, Yamamoto, & Higuchi, 2016). Yet, other important aspects of embodiment and bodily self-consciousness are arguably connected to more global aspects of the self (e.g., Blanke & Metzinger, 2009), involving full-body control and feedback from the entire body. Empirical studies



FIGURE 1 Examples of human–machine interfaces and human-in-the-loop experiments. Top: Intention recognition by tactile sensing (left), inertial measurement units (left middle), and electromyography (right middle) as well as haptic feedback (right). Bottom: Virtual reality environment for upper limb prosthetic research, robotic leg illusion (middle), robotic numbness illusion (right)

have thus extended rubber hand illusion-like paradigms to video and virtual reality setups to investigate the underlying mechanisms (Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Petkova & Ehrsson, 2009; Ionta et al., 2011; Maselli & Slater, 2013).

Recently, the phenomenon of co-adaptation receives distinct interest in robotics, which also seems to link HRI to embodiment. Co-adaptation is the process through which the robotic device adapts to its human operator/user *while* the human adapts to it. Both phenomena can be measured: the devices might tune their own parameters through adaptive calibration and/or machine learning while the operators would improve their own motor skills (in practice, improving/shifting/spreading the own signals generated to control the device) and sometimes even their perception, to better control it (Antuvan, Ison, & Artemiadis, 2014; Hahne, Dähne, Hwang, Müller, & Parra, 2015). For instance, it has been shown that while a short delay between a motor intent and the experienced consequence is crucial for the sense of agency in general (e.g., Haggard, 2005), participants might adapt to longer delays under certain conditions (Haering & Kiesel, 2015), and feel less agency when provided with immediate feedback. Through the robot and the interface, co-adaptive processes might thus influence both the perception of and the interaction with the environment and the operator. Co-adaptation hence exhibits a great potential to alter the sense of a bodily self and consequently embodied cognition (Rosen et al., 2009; Hara et al., 2015; Rognini & Blanke, 2016; Beckerle et al., 2017).

Human-in-the-loop experiments with robotic devices (see Figure 1 and Box 1), hence, facilitate the study of how a device can be embodied by the human operator through co-adaptation, for example, concerning control delays or types and qualities of feedback over time. To answer research issues on full-body level, exoskeletons might importantly extend the methods discussed previously (Aymerich-Franch, Petit, Ganesh, & Kheddar, 2016). From an engineer's point of view, this can pave the way to a new generation of control methods and shed light on the advantages and disadvantages of (semi-)autonomy of the robot. From the perspective of a psychologist or neuroscientist, it opens the above-mentioned “window” onto the human mind, embodiment, and embodied cognition. An interesting example of such virtuous interaction has been explored for decades in the realm of robotic-aided rehabilitation (Reinkensmeyer & Patton, 2009; Tzorakoleftherakis, Murphey, & Scheidt, 2016; Rowe et al., 2017; Pierella et al., 2017). In particular, the phenomenon of “body space reorganization” observed after repeated usage of spinal cord injury rehabilitation devices (Pierella et al., 2017) look similar to the embodiment of mechanical artifacts, and—we speculate—stems from co-adaptation between the patient and the rehabilitation device. As a result, interdisciplinary research questions that require joint activities of researchers from both fields emerge:

BOX 1 HUMAN-IN-THE-LOOP EXPERIMENTS

Human-in-the-loop experiments are paradigms that let human participants experience mechatronic and robotic technology, for example, to test the control performance of exoskeletons or prostheses (Gopinath et al., 2017; Zhang et al., 2017). Participants are therefore equipped with the investigated technical device and become part of the human–machine system and its control loop. Due to the direct interaction of both partners, such experiments can yield detailed information during the usage, which might not be captured by postexperiment questionnaires or measures. This might even be performed done during development to guide the design in a user-centered direction. Recently, neuroscientific research started to exploit these type of experiments to understand the human bodily self (Rognini & Blanke, 2016; Beckerle, De Beir, Schürmann, & Caspar, 2016). Here, the experiments open up completely novel possibilities: for instance, they allow to disentangle action and perception by altering the control of the robot and the sensory feedback to the human through programming, for example, adding delays or manipulating haptic rendering. In contrast to virtual reality approaches, the design of robotic human-in-the-loop is more complex (Beckerle et al., 2016; Beckerle, Bianchi, Castellini, & Salvietti, 2018), but it enables long-term stimulation similar to traditional or virtual environment embodiment paradigms, while advancing our understanding and the improvement of technical implementation.

- How much does the subjective feeling of embodiment increase the finesse and dexterity of intent detection? Does an embodied device elicit more/better signals?
- How precise does sensory feedback have to be to increase embodiment, for example, temporally, spatially, and regarding modality? To what extent is it task-specific?
- How do different facets of sensory perception, for example, affective touch and high-resolution feedback, foster embodiment?
- How does the temporal dynamics of co-adaptation influence probabilistic body representations regarding bottom-up sensory integration and top-down expectancies, that is, to what extent can humans adapt via learning mechanisms?
- Which individual factors influence mutual adaptation and embodiment? How are cognition and emotion influenced?

As stated above, we necessarily see a dexterous, transparent HMI that carries information in both ways (Beckerle et al., 2017; Castellini et al., 2014) as the core aspect of technical integration. Via an *efferent* channel, human intent needs to be detected through biosignals and communicated to the robotic device. Through an *afferent* channel, the bodily perception and experience of the human needs to be stimulated to induce sensory substitution/enhancement. The task of such a bHMI is extremely challenging: it must operate seamlessly, reliably, and in real time to foster adaptation in complex environments. Hence, we subsequently analyze what is still missing and highlight necessary steps toward the deployment of effective bHMIs.

3 | CURRENT LIMITATIONS

As a distinct example of HRI with great relevance both for fundamental and applied research regarding the above-mentioned questions, we consider *upper-limb prosthetics* (see Box 2). Upper-limb prosthetic control requires input in form of bodily signals, which are inherently variable. Yet, it must deliver close-to-100% reliability and, moreover, provide nonvisual feedback—the perfect application for a bHMI. Still, nowadays a substantial number of individuals with amputation abandon their prostheses (Peerdeman et al., 2011; Micera, Carpaneto, & Raspopovic, 2010; Engdahl et al., 2015; Jiang, Došen, Müller, & Farina, 2012), as they still experience phantom-limb sensations and pain (Lenggenhager, Arnold, & Giummarra, 2014). Even with the newest techniques, many users cannot properly operate costly robotic devices as if they were their own limbs (Niedernhuber, Barone, & Lenggenhager, 2018). They thus appear to not meet the criteria to be embodied. The clinical truth is sad: at the 2016 Cybathlon ARM competition, the two winning approaches were traditional one-degree-of-freedom body-powered grippers¹ (Makin, de Vignemont, & Faisal, 2017). The gap in reliability between the traditional and the *technologically* more advanced techniques was apparent.

More generally, the ideal bHMI would be usable in a number of diverse scenarios beyond upper-limb prosthetics: an interesting example is (anthropomorphic) *robotic teleoperation*, where a human operator remotely controls a robotic limb via moving the own corresponding limb, for example, a robot arm in space. While reliability might be less relevant than in prosthetics due to the lack of potential harms to the user, the other requirements are rather similar: input signals might vary, for example, when using electromyographic sensors for intent detection, well-engineered transparency (Pacchierotti, Tirmizi, & Prattichizzo, 2014), and nonvisual feedback would be very supportive for the user. Interestingly, performance, accuracy, and dexterity in physical tasks seem to relate to the sense of agency (Kiltner, Groten, & Slater, 2012) and to body schema integration (Haans & Ijsselstein, 2012). These aspects of bodily experience are crucial for tool usage (Holmes & Spence, 2004) and, moreover, humans are capable to utilize tools as sensory extensions of their bodies (Miller et al., 2018), which both substantiate the immense potential of bHMIs. For instance, bHMIs could yield improved embodiment of remotely controlled robots by providing users a sense of agency (Kiltner et al., 2012). Beyond agency, appropriate interfaces might provide users with an improved awareness of their bodies and peripersonal spaces in the remote environment (Haans & Ijsselstein, 2012; Cléry & Ben Hamed, 2018).

Obviously, a significant research effort is still required: there is neither any agreement on the ideal intent-detection and feedback method, nor does research sufficiently consider how to reliably and unobtrusively connect the hardware to the human body (Castellini et al., 2014; Rognini & Blanke, 2016). This is ultimately irrespective of the application and applies to prosthetics and teleoperation as well as to many other assistive robotic devices, for example, exoskeletons (Beckerle et al., 2017). Besides sensory substitution, this might extend HRI in terms of nonverbal communication since force and tactile

BOX 2 PROSTHETICS

Prosthetics is probably the paradigmatic application of robotics in which the role of embodiment, immersion, and closing-the-loop is paramount. A prosthesis is expected to be worn continually and it ultimately should feel as closely as possibly as the user's limb. Still, unreliability of control, insufficient dexterity, physical discomfort caused by the device and lack of (complex) sensory feedback are factors which hamper embodiment of prosthetic devices (Castellini, Bongers, Nowak, & van der Sluis 2015; Niedernhuber et al., 2018).

A better understanding of the fundamental cognitive mechanisms of the bodily experience of wearable robotic devices seems to be a very promising way to improve the design of prosthetic hardware and the related bHMIs (Christ et al., 2012; Rognini & Blanke, 2016; Beckerle et al., 2017). Research on embodiment also potentially sheds light on how to design novel experimental and functional assessment protocols: prosthetics research must get out of the laboratories and dive deep into daily living activities. As an intermediate step it could be interesting to develop and empirically investigate more realistic and complex paradigms such as the numbness illusion (Dieguez, Mervier, Newby, & Blanke, 2009) and their implementation in human-in-the-loop experiments (Huynh et al., 2018).

information can support contact/motion analysis and planning (Beckerle et al., 2017). Many crucial issues are by far not solved, for example, commercial upper-limb prostheses only restore extremely limited functionality, which might impede embodiment.

While hardware-related problems can partially be circumvented in virtual reality experiments (Mercier & Sirigu, 2009; Ortiz-Catalan et al., 2016), there is currently no bHMI on the market that meets the requirements mentioned above in everyday applications. These problems apply to all mentioned types of (assistive) robotic devices and resurface whenever semi-autonomy is necessary in HRI, for example, due to the unpredictability and nonmodelability of the operator/environment (Castellini, 2016; Gopinath, Jain, & Argall, 2017).

As far as bHMI technology is concerned, there is a growing interest in high-resolution bodily sensing and feedback, and we believe this is a path that deserves to be explored. For instance, the human arm/hand system is comprised of hundreds of thousands of axons pertaining to both sensorial and motor neurons (Gesslbauer et al., 2017) that facilitate manifold and sophisticated human perception. Moreover, modern machine learning methods can quite easily handle high-dimensional data, and *exploit the redundancies* found among them. Due to these reasons, high-density surface electromyography (HD-sEMG) as well as tactile sensing have already been investigated out in academic environments (Ison, Vujaklija, Whitsell, Farina, & Artemiadis, 2016; Radmand, Scheme, & Englehart, 2016; Nissler, Connan, Nowak, & Castellini, 2017). In addition, electrocutaneous (Franceschi et al., 2017) feedback with high spatial resolution and biomimetic coding techniques for natural feedback are (Valle et al., 2018) being explored. What is missing so far, we believe, is a tighter integration of the approaches serving the efferent and afferent channels, which might lead to unprecedented results. While many technologies are being developed separately from each other, this integration of recently developed sensors and stimulators appears paramount to achieve high levels of embodiment.

As a basis of our suggested research roadmap, we show a schematic representation of the current situation in the leftmost column of Figure 2 (the now region): *high-density (HD) intent detection and feedback* are still in their infancy, very far from clinical practice and/or from commercial ripeness; and besides that, they are still independent of each other. As far as *control* is concerned, it appears fundamental to take into account that HRI involves two closed loops, the mechatronic and sensorimotor one, which should be interconnected. On the one hand, the mechatronic loop is standard closed-loop control of the hardware, for example, position, velocity, force, etc. Although closed-loop hardware control with onboard sensors is a common practice in industrial robotics, this is definitely not the case in prosthetics for instance (Makin et al., 2017). The sensorimotor loop, on the other hand, is the tight integration of human action and bodily feedback, which might also be bypassed by neuroprosthetics (Blumberg & Dooley, 2017). Interestingly, the only type of commercially available devices which enforce the sensorimotor loop appears to be body-powered prostheses such as those that dominated at Cybathlon. These devices intrinsically provide force feedback, which could be seen as an indicator of the importance of interaction and outlines the potential issues occurring due to limited or missing connections in and between both control loops.

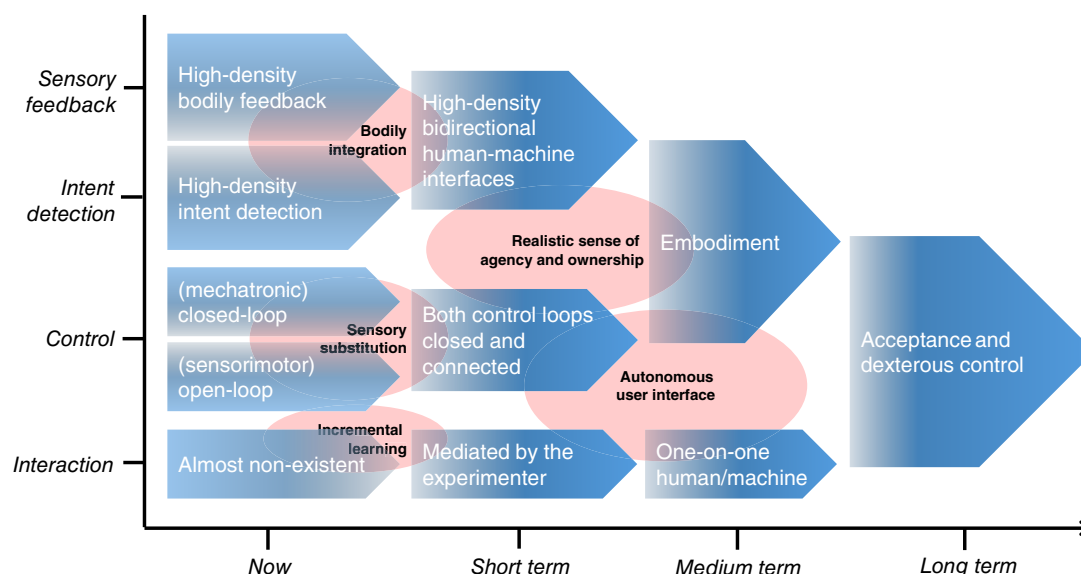


FIGURE 2 The research roadmap suggested to understand and develop bidirectional human-machine interfaces that enable robotic experiments, which advance the investigation embodiment and embodied cognition

4 | RESEARCH ROADMAP

Considering state of the art research, Figure 2 outlines our suggested roadmap for short-term, medium-term, and long-term developments.

In the short term, fostering an integration of the HD intent detection and HD feedback approaches is expected to enable bodily integration in terms of ownership and agency, both important aspects of embodiment (Tsakiris, Schütz-Bosbach, & Gallagher, 2007). Technically, robotic skins (Le, Maiolino, Mastrogianni, & Cannata, 2016) and HD tactile-sensing arrays for intent detection (Büschler, Kõiva, Schürmann, Haschke, & Ritter, 2015), as well as wearable haptic devices (Pacchierotti et al., 2017) and HD electrical feedback (Strbac et al., 2016; Franceschi et al., 2017) are promising examples. While data from classical HRI studies should be taken into account for designing future bHMIs, we expect the testing of new bHMI devices to reveal how control and feedback designs influence embodiment in a much more fine-grained manner, for example, with respect to control delays and feedback modalities. Regarding the modalities, the interplay of multiple sensory stimuli (Berniker & Kording, 2011) needs to be considered, as the example of the rubber hand and related illusions indicate (a probabilistic integration of vision, touch, and proprioception). A recent study (Berger, Gonzalez-Franco, Ofek, & Hinckley, 2018) substantiates that congruent visual and haptic stimuli enhance the subjective experience during a task in virtual reality. In contrast, incongruent visual and haptic stimuli can worsen perceived embodiment to an even greater degree than simple haptics.

At the same time, a fruitful interaction between the mechatronic and sensorimotor loop can and should be explored. Here as well, we postulate that sensory substitution might be a key to connect both loops and thereby could support the bodily integration (Beckerle et al., 2017). The degree of autonomy of the machine, as well as its ability to self-regulate (mechatronic loop) should be somehow modulated by the degree of *trust* that the operator puts in it: the more the outer sensorimotor loop induces embodiment and trust, the less autonomy is required of the artifact. However, even in the case of a high degree of embodiment, it might still be desirable to devolve some specific tasks to the machine itself (Argall, 2015), for example, to firmly grasp an egg with a grip-lock mode that does not adapt the grasping force of the prosthesis. Interaction is a key aspect of the simultaneous growth and adaptation of human and machine and may take place in various forms, which needs to be explored in more detail. A first step could comprise requests and interventions by the user to correct the behavior of the machine, probably under laboratory-controlled conditions and mediated by an experimenter.

Through fostering bodily integration by mutual control through human and machine, the *medium-term* aim of a realistic sense of agency and ownership should be achieved. This appears to be a major challenge since psychological and physiological aspects need to be considered when connecting the loops and interfacing them to the detection and feedback devices. The complexity of this challenge is underlined by a recent single-participant long-term experiment, which did not show significant differences in embodiment between open- and closed-loop operation (Page et al., 2018). Moreover, nuances of bodily sensations such as affective touch that comprise not only cognitive but also emotional aspects need to be considered (Crucianelli, Metcalf, Fotopoulou, & Jenkinson, 2013; van Stralen et al., 2014). In parallel, we envision that a comprehensive interaction of human and machine can be reached using an autonomous user interface together with mutual control. For instance, the machine could *request* that the operator performs or repeats a certain task, in order to improve its own model of the world, for example, by incremental learning (Pilarski, Dawson, et al., 2013; Pilarski, Dick, & Sutton, 2013; Nowak, Castellini, & Massironi, 2018). A major hurdle in this endeavor is potential interference between semi-autonomy and embodiment (Beckerle et al., 2017; Beckerle, 2017).

Once we start fostering co-adaptation we should also be able to measure it as well as encourage users to exploit it. To this end, several measures have been proposed in recent literature (Antuvan, Ison, & Artemiadis, 2014; Hahne, Dähne, Hwang, Müller, & Parra, 2015; Nowak, Bongers, van der Sluis, & Castellini, 2017). In all cases clear learning curves have been identified, both in terms of improved performance and change in the ways human users approach the machines, but little is known on how it influences specific aspects of embodiment. For instance, it is common to notice a change in the separability of signal patterns in the input space after repeated activity is carried out. Finally, learning mechanisms have been shown to be important for basic aspects of embodiment such as the feeling of agency (Haering & Kiesel, 2015) and thus require special attention.

As soon as full-scale embodiment of robotic devices is possible through such bHMIs, we envision that this will allow for dexterous control and thereby, finally, improve user acceptance. Moreover, the value of bHMIs and robotic devices as research tools for cognitive psychology and consciousness research will distinctly exceed the current situation. Our roadmap contributes a direction for this development and serves as a basis for future scientific discussion.

5 | CONCLUSIONS

The rapid advances and high variety of human-machine interfaces (HMI), especially in the field of robotics, call for an intense collaboration between engineering and (neuro-)psychological sciences. The former drives to overcome current limitations with

technical solutions while the latter starts using the developed technologies to better understand the human brain and mind. We argued that the currently probably most interesting, but also the technically most demanding devices in that field are bidirectional HMIs, which detect the human's intent simultaneously and in real-time to provide feedback. Promising developments in this direction are wearable haptic devices, robotic skins, and HD tactile sensors and stimulators. Although technology is advancing quickly, for example, providing miniaturized and flexible actuators and sensors (Kim et al., 2014), bHMIs that process and handle information in a human-like fashion are still rather far from realization. Yet, even bHMIs that only roughly approach human-like capabilities would advance the proposed roadmap, which might actually become some kind of research cycle. For control design, aiming at device embodiment sets high requirements since designers need to seriously consider the cognitive abilities of both interaction partners to avoid the user from feeling to be controlled by the semi-autonomous machine.

The optimization of such bidirectional HMIs is not only extremely important for applied sciences (as we exemplified at the development of upper-limb prosthetics), but also opens up new ways to study the human brain and its plasticity. Moreover, appropriate control through advanced bHMIs might even allow going beyond the biological possibilities of humans, for example, by enabling the embodiment of supernumary limbs (Kannape & Lenggenhager, 2016; Parietti & Asada, 2016; Sasaki, Saraiji, Fernando, Minamizawa, & Inami, 2017; Masia et al., 2018). Current experimental paradigms used to study the plasticity of the bodily self and underlying adaptive processes are rather simple and limited both in experimental control as well as duration of stimulation. The inclusion of contemporary HMIs in neuropsychological studies will allow on one hand a very specific control of different parameters, for example, sensory versus motor mechanisms, and on the other hand the possibility to conduct more long-term studies. Understanding how and to what extent a robot might be integrated into the human self and alter cognitive processes will extend current knowledge in this field.

The future aim will be to identify the crucial parameters both on the human as well as on the machine side, to understand adaptive process, and to develop bHMIs which enable both maximal control as well as maximal acceptance.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

ENDNOTE

¹<http://www.cybathlon.ethz.ch/about-us/cybathlon-2016/results-2016/arm-results.html>

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ORCID

Philipp Beckerle  <https://orcid.org/0000-0001-5703-6029>

Claudio Castellini  <https://orcid.org/0000-0002-7346-2180>

Bigna Lenggenhager  <https://orcid.org/0000-0003-0418-9931>

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