Next Steps in Human-Computer Integration

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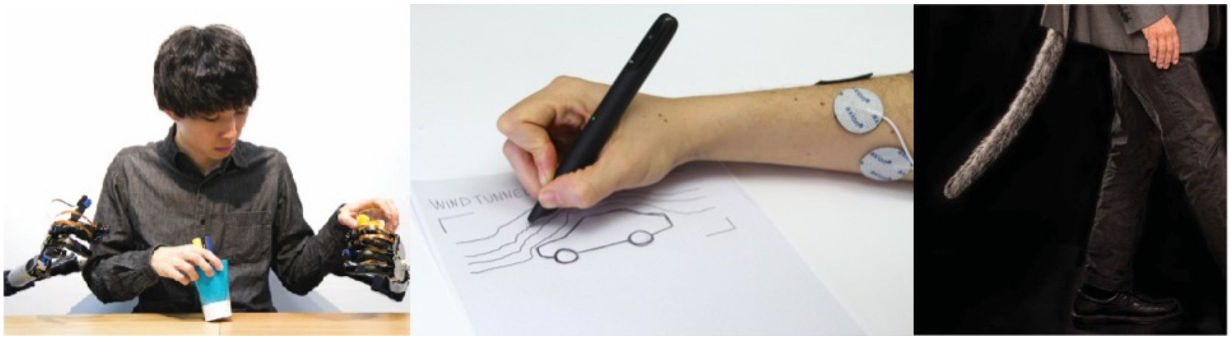

Figure 1. Exemplars of Human-Computer Integration: extending the body with additional robotic arms; [70] embedding computation into the body using electric muscle stimulation to manipulate handwriting [48]; and, a tail extension controlled by body movements [86].

ABSTRACT

Human-Computer Integration (HInt) is an emerging paradigm in which computational and human systems are closely interwoven. Integrating computers with the human body is not new. However, we believe that with rapid technological advancements, increasing real-world deployments, and growing ethical and societal implications, it is critical to identify an agenda for future research. We present a set of challenges for HInt research, formulated over the course of a five-day workshop consisting of 29 experts who have designed, deployed, and studied HInt systems. This agenda aims to guide researchers in a structured way towards a more coordinated and conscientious future of human-computer integration.

Author Keywords

Integration; augmentation; cyborg; implants; bodily extension; fusion; symbiosis

CCS Concepts

•Human-centered computing → Interaction paradigms;

INTRODUCTION

In designing the future of computing, it is no longer sufficient to think only in terms of the *interaction* between users and devices. We must also tackle the challenges and opportunities of *integration* between users and devices. This perspective is essential to fully understand and co-shape technology where user and technology together form a closely coupled system within a wider physical, digital, and social context.

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Looking at past eras of computing, these typically have a unique ratio of users to computers as one of their identifying feature: The mainframe era of one-machine-to-many-users shifted to the one-machine-to-one-user era of the personal computer, followed by the one-user-to-many-machines era of mobiles, to finally the many-machines-to-many-users era of today's ubiquitous computing era [96] (Table 1). Looking towards the future, however, it appears that the next era will not be described by such a ratio, but rather that its distinguishing feature will be the *blurring* of the boundary between human and computer [46].

Era / Paradigm	Users : Machines
Mainframe	many : 1
PC	1 : 1
Mobile	1 : many
Ubiquitous	many : many
Integration	**blurred boundary**

Table 1. Eras of Human-Computer Interaction.

We call this *Human-Computer Integration* (HInt) and consider it a new paradigm with the key property that computers become closely integrated with the user. Such integration occurs primarily at an individual level through *sensory fusion*, with computers providing information directly to human senses rather than through symbolic representations and understanding the user's implicit, precognitive needs through bio-sensing. However, we also note that this integration happens at a societal level, where human and interface agents display *coordinated effort* towards achieving a common goal.

As such, HInt research shifts the focus of HCI away from the question *"How do we interact with computers?"* towards *"How are humans and computers integrated?"*. In this paper, we present key challenges identified in a 5-day workshop with the aim of moving the field forward. We believe this provides HCI researchers with a set of challenges to guide their future work in a coordinated and conscientious manner. We believe that such a structured approach is preferable over, for example, following industry trends or financial short-term gains.

Although prior work has discussed challenges in related [19] and overlapping areas (e.g., cybernetics [6, 43], intellect augmentation [18, 65, 50], cyborgs [13], wearables [80, 78, 45]), we have not yet seen any articulation of the key challenges facing HInt. Unlike most of the prior theoretical work above, our work does not stem from an individual mind, but rather from a collective group of people who have developed an understanding of HInt through their own practice, coming from a wide range of backgrounds. Therefore, our work presents a collective set of future steps coming from the "trenches", which aims to extend prior road maps by articulating road blocks we found along the way.

Our key contribution is the synthesis of the challenges that the human-computer integration field faces across four thematic areas: (1) Human-Compatible Technology; (2) Effects of Integration on Identity and Behavior; (3) Human Integration and Society; and (4) Designing Integrated Interaction. This will help researchers and practitioners interested in HInt to: (a) identify current knowledge, capabilities and areas of opportunity where they can contribute; (b) situate their work within a larger HInt research agenda; (c) and also allow policy makers to better understand the HInt community, state-of-the-art technology and research, as well as potential applications.

PROCESS

To formulate the challenges for Human-Computer Integration, we organized a 5-day workshop with 29 participants.

Participants

Our participants included 19 senior academics, 5 senior industry participants and 6 junior academics. Participants represented broad areas of expertise across computer science, design, art, psychology in areas including human computer interaction, mobile, wearable, printed electronics, haptics, multisensory experiences, gaming, user experience design, cognitive psychology, social psychology, and multimedia art. Nine participants identified as women and 20 as men. Participants were distributed throughout the globe (Europe 9; North America 12; Asia, 2; Australia, 6) and across a range of ages (21-30, 4; 31-40, 8; 41-50, 9; 51-60, 4; 61-70, 4).

Participants were invited because they have designed, taught, deployed or studied HInt systems. Examples of such systems are depicted in Figure 1. For instance: MetaArms, a system that augments the user's body with two additional robotic arms controlled by the user's feet to allow handling complex tasks that two hands might have difficulty with [70]; Muscle Plotter, a system that uses electric muscle stimulation (EMS) to turn the user's wrist into a computerized pen plotter, allowing to draw, for example, simulated wind effects on the shape of a car's sketch [48]; or a motion-controlled tail extension to the wearer's body, which can be used for enriched self-expression either in daily life or as part of artistic performances [86].

Discussion process

Prior to the workshop, participants shared with the group 1-2 seminal readings related to Human-Computer Integration. The 5-day workshop began with a Pecha Kucha where each researcher presented their research related to the topic of Human-Computer Integration and the seminal reading(s) they selected. Subsequently, we broke out into subgroups (4-5 participants each) to explore: Key Challenges, Definition of HInt, Motivations for HInt and Dark Patterns and Ethics; following each of the break-out sessions, the groups would re-convene to share insights and findings for discussion with the larger group. Participants would rotate between subgroups to share their expertise. In addition, there was a generative design session which also took place in sub-groups, with a subsequent guided reflection on the theoretical topics that emerged. These insights led to the creation of a collaborative document in which authors refined the key challenges and insights that would ultimately be shared with the HCI community.

RELATED WORK

The idea of integration between a system and their user can be traced back in the history of computing, art, philosophy, neuroscience, and even science fiction. In this paper, we focus predominantly on the perspective taken by researchers in HCI. Therefore, we review prior work that inspired and grounded our research mostly from this lens. Note that we kept this section intentionally short as throughout our following argumentation we bring up the relevant references in our discussions.

Tracing back the precise origins of the concept of "integration" is outside the scope of our work as we intend to focus it on the direct challenges this concept poses for the field of HCI. Yet, we briefly illustrate how this concept originated in various shapes and in a wide variety of knowledge fields. The concept itself can be seen in science fiction, in concepts, such as "man-machine mixture" in Edgar Allan Poe's writing in 1843 or the humanoid-"robot" in Karel Capek's 1920s play; in neuroscience where Manfred Clynes and Nathan Kline coined the term cyborg in the 1960s; philosophy, as echoed in D. S. Halacy's 1965 essay on the Cyborg; art, for example in Stelarc's 1990s work, and, of course, in early works in human-computer interaction, which we detail in the following.

Examples of devices integrating with the user's body can be traced almost to the start of the field of interactive computing, which was empowered by derivative ideas from Norbert Wiener's cybernetics movement, such as closed-loop machine systems [36]. One canonical example is Licklider's "(Hu)man-Computer Symbiosis", which, building on the cybernetics ideas, postulated that "the cooperation between users and machines was an expected development", and, moreover, that this would require a "very close coupling between the human and the electronic member of the partnership", alluding to notions of body-integration [43]. Another seminal example is Engelbart's vision of HCI as "augmentation of human intellect" [18]. This was well depicted in Engelbart's GUI system, designed in 1960s, attempting to not only simplify input (using the mouse and a chorded keyboard) but, also, to amplify a user's cognitive abilities. These ideas were echoed in other prototypes of the time. For instance, Sutherland's "ultimate display" was not only a critical advancement in display techniques but an attempt to fuse the human spatial senses (not only vision, but also proprioception) with that of the device [85]. From here on, the list of examples runs long and we will refer directly to these as they assist our argumentation.

TYPES OF HUMAN-COMPUTER INTEGRATION

While the concept of integration between humans and computers echoes the initial efforts of pioneers, such as Licklider [43], Engelbart [18], and even Clark [13], it is Farooq and Grudin's more recent articulation of human-computer integration [19] that we use as point of departure. We expand upon Farooq and Grudins work to include other aspects of integration, which we consider to be particularly relevant.

Integration between humans and technology can occur and has already occurred in many ways. When we speak of HInt systems, we refer to a subset of these. Figure 2 shows an overview of ways in which technology and humans can integrate. The x-axis depicts *agency*; ranging from devices in which humans are in full control (left), to shared control (middle), and to systems in which all control remains at the device (right). The y-axis represents the scale at which the *integration* occurs: ranging from whole cultures integrated with technology (top), to organs and organelles at the micro level of integration (bottom). Together, these two dimensions map out a subset of ways in which humans and technology can relate. Our primary interest lies in two types of integration that we will describe next, these are: *symbiosis* and *fusion* (indicated in horizontally stripped purple and vertically striped blue, respectively).

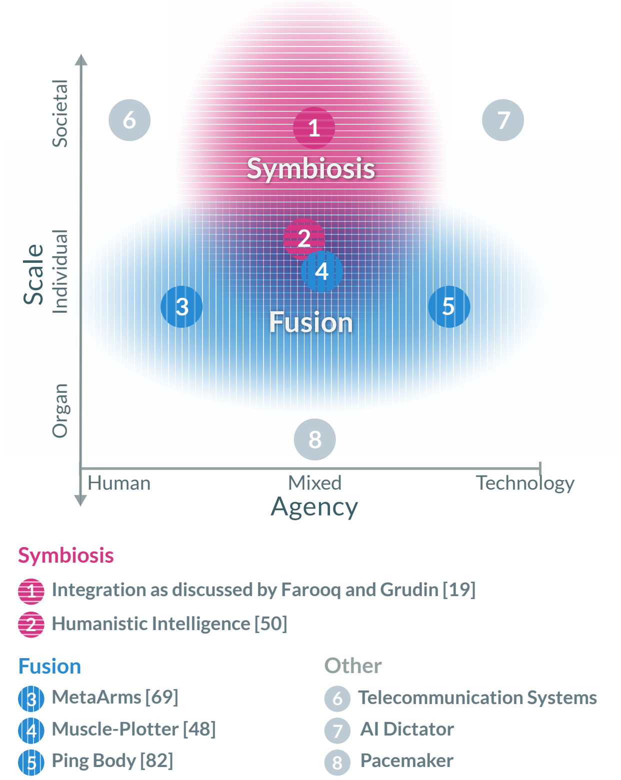

Figure 2. Map of integration between humans and devices.

Symbiosis

We call systems in which humans and digital technology work together, either towards a shared goal or towards complementary goals, *symbiotic* (Figure 2, purple). In this type of integration, agency is shared between humans and digital systems, and integration can occur on the individual level or between groups of people and technological systems. Examples of symbiosis, depicted in Figure 2, include: ① the scenarios presented by Farooq and Grudin [19], which describe digital systems, which continuously work on the humans behalf, even when the human is not attending them. Their examples include integration beyond the individual level, as activities such as autonomous driving or intelligent rescheduling of meetings, require technologies to mediate between multiple people and ② at an individual level, Mann's vision of Humanistic Intelligence [50] where there is a continuous feedback loop between a human and a digital system, each augmenting the other.

The key characteristic of symbiosis is not that computers enable software agents or that the agents are smart. The key is that the agency is truly shared between technology and humans acting in concert, for example by collaborating in creative tasks [23, 10] or working together towards engaging experiences [5]. This excludes various ways in which technology is currently integrated in our society, for example ⑥ telecommunication technologies have become an integral part of our culture, yet they do not have any agency of their own. Similarly, ⑦ a future where the government is replaced by AI agents which dictate human laws, would also not be considered symbiosis as the agency of the human is lost.

Fusion

We define *fusion* as an integration in which devices extend the experienced human body or in which the human body extends devices (Figure 2, blue). Fusion occurs on an individual level and often only affects a sub-part of the user, such as a limb or a sense. Unlike symbiosis, which requires shared agency, fusion can occur throughout the spectrum of agency. A key characteristic of fused systems is information that is not represented symbolically. Instead, humans perceive through fusion systems by embodied mediation [92]. Similarly, fused systems do not require explicit input from humans, but simply act as extensions of human bodies.

Examples of fusion systems, depicted in Figure 2, include: ③ MetaArms [69] (depicted also in Figure 1), a system in which the agency is almost entirely with the user, but the technology feels like a natural extension of one's body; ④ Muscle-Plotter [48], a system that controls the user's hand via electrical muscle stimulation to empower the user with computer based simulations (also depicted in Figure 1); and, ⑤ Ping Body [82], an art piece by Stelarc in which the performer's body is controlled by via muscle stimulation in a way that only minimal agency remains with the human. Fusion might also occur with implanted devices [28, 84], ingested devices [41, 81], or epidermal electronics [80], as well as devices which extend or manipulate the body (e.g. [86, 74]), or stimulate the senses [47, 73, 83, 98].

Not all systems where technology and the human body physically connect fall within our definition of fusion. For example, devices which augment individual organs below the perceptual threshold, such as ⑧ pacemakers are also outside of the scope of HInt as we present it. While literal integration occurs due to the implantation, these devices do neither provide an interface to the user nor provide the user with any agency.

HInt as Analytical Lens

When we speak of Human-Computer Integration, we explicitly refer to both *fusion* and *symbiosis* [1]. Fusion and symbiosis should not be understood as supported by a specific technology, rather they describe ways in which humans and technology relate. HInt then becomes an analytical lens for analysing and designing such relations, whereas Human-Computer Interaction (HCI) is a broader lens for analysing and designing interfaces of various types.

The HInt and the HCI lenses can be used for analysing the same scenario, e.g., a user with an exoskeleton [69], but each sheds light on a different aspect. The key difference is that the HInt lens considers as its starting point that we are observing *one* human-technology assemblage; instead of considering that we observe an *interaction* between the user and the exoskeleton–this would be the result of looking through the more general HCI lens. Therefore, the HInt lens encourages analysis of this human-technology assemblage, for example, by asking how the agency is distributed or by describing the type of integration by measuring the amount of physical or cognitive coupling between user and interface.

CHALLENGES

Shneiderman et al. [75] suggested that HCI as a field needs "grand challenges" to steer the direction of future research, design, and commercial development. As such, challenges have been articulated across respective fields, see, for example, the work on next steps and challenges within shape-changing interfaces [3], information retrieval work [7], social robotics research [89], and crowdwork investigations [37]. Just as they have advanced their respective fields, we hope that our work will move the HInt field forward. In this paper, we describe four sets of challenges that we expect to be at the core of future HInt research: (1) Human-Compatible Technology; (2) Effects of Integration on Identity and Behavior; (3) Integration and Society; and (4) Designing Integrated Interaction". We describe these next.

CHALLENGE #1: HUMAN-COMPATIBLE TECHNOLOGY

We believe that, especially due to the fusion between computer and human body, HInt systems will benefit from a deeper understanding of the user's physiological and mental state. This understanding requires collecting and interpreting data from the human body. For example, the combination of biochemical and electrophysiological signals allows devices to reason about the user's health and fitness [31] (see Figure 3 for more examples). However, current systems, such as wearables, are often designed around a rigid form factor that restricts their placement in the user's body. Hence, they can only access a limited amount of information and are not well integrated into the body.

In recent years, advances, such as epidermal electronics and interactive textiles have emerged that make use of flexible and stretchable electronics, which enable stronger fusions with the human body. Beyond the material aspects, the integration of electronics with the body raises the need for customising for different body sizes and shapes as well as personalising that will allow people to express themselves and their aesthetic preferences. Moreover, the integration with the body requires rethinking how devices are deployed, maintained, and connected to their surroundings. We therefore structure this section of human-compatible technology into key types of human-compatible technology, materials for integration, tailored technologies for the body, and connecting the body and the world.

Key types of human-compatible technology

We identified five key types of human-compatible technology, noting that future devices could act across multiple layers at once (see Figure 3 and Table 2).

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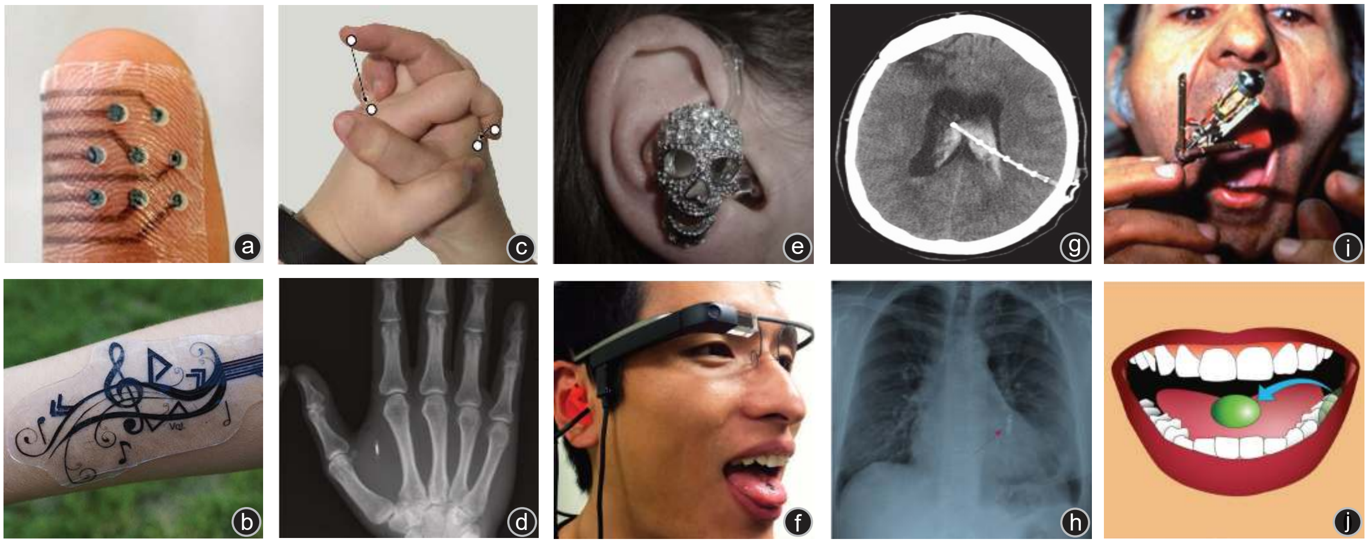
[1] In our subsequent analysis, we mostly highlight fusion aspects over symbiosis, as we found these to be less prevalent in prior discussions of integration [19, 21, 20].



Epidermal Technologies Subdermal Technologies Transdermal Technologies Implanted Technologies Pass-through Technologies

Figure 3. Examples of human-compatible technologies. (a) Tacttoo [97], (b) iSkin [94], (c) Hobbyist use of insertable devices [27], (d) RFID implants [24], (e) Wear It Loud [64], (f) The tongue and ear interface [68], (g) Cerebral shunts [76], (h) pacemaker [87], (i) Stomach Sculpture [81], (j) ChewIt [22].

Type	Body Contact	Application	Permanence	Maintenance	Lifetime
Epidermal	Epidermis	User-controlled (sticker, spray-on)	Removable by the user	Removable and replaceable	User-controlled, allows for short term usage
Transdermal	Epidermis and dermis	Piercing or surgery	User-controlled or surgery	Through external port	Medium to long-term usage
Subdermal	Dermis	Syringe or small surgery	Permanence through surgery	Through surgery or wireless update	Medium to long-term usage
Deep Implanted	Internal organs	Surgery	Permanence through surgery	Through surgery or wireless update	Long-term usage
Pass–Through	Digestive system	User-controlled	No	Not intended: wait till it passes through	Usually 24-26 hours

Table 2. Key types of human-compatible technology and their properties.

Epidermal technologies are worn on the skin. In contrast to wearable devices, their thin and stretchable form factor enables them to better integrate into human skin. Examples of such technologies in interactive devices include: iSkin [94], Skintillates [44] DuoSkin [33], and SkinMarks [95]. These devices offer users a variety of applications, such as on-body input [94, 44, 33, 95, 58], on-body NFC [33], visual displays [95, 33] and haptic output [97, 98]. Their main advantage is their easy application and removability.

Subdermal technologies integrate devices into a deeper layer of the skin: the dermis. In contrast to epidermal technologies, these technologies can access more body information, e.g., by analyzing the interstitial fluids. For example, Holz et al. investigated the feasibility of interacting with subdermally implanted touch sensors, LEDs, vibration motors, and microphones [28], and Heffernan et al. surveyed hobbyists' use of many subdermal devices [27].

Transdermal technologies contain an epidermal and subdermal part, similar to a piercing. They combine several advantages of the previous technologies, i.e., they enable a deeper integration with the body while supporting easy access from outside the body. Body parts that allow for piercing (e.g., the ear and the nose) can host electronics that are still easily removable. Transdermal objects, common in the body modification scene, open a path from the outside to the inside of the body but require constant care to avoid infections.

Deep implanted technologies are permanently inside the human body (e.g., a pacemaker or an insulin pump). These devices can have the deepest integration with the human body, but they are hard to replace, and application requires surgery. Homewood and Heyer explored how users might want to interact with such devices [29].

Pass-through technologies are technologies that enter the body only for a specific duration. The advantage is that these devices automatically exit the body or dissolve after a certain time. Examples include digested pills that are able to track body temperature [41, 42], chewing-gum-like interfaces that provide hands-free interactions [22], and some early artistic performances by Stelarc [81].

Having discussed key technologies for human-compatible technology, we now turn to the materials required to make this integration with the human body successful.

Materials for Integration

We find that a close integration with the human body benefits from devices that feel and behave like parts of the body. For such devices it is beneficial to be biocompatible, miniaturized and, deformable, three aspects we discuss next.

Biocompatibility: Due to their close proximity to the human body, integrated devices require a higher level of biocompatibility than traditional interactive devices, such as mobile phones, smart watches, or head-mounted displays. For example, an integrated implant should not expose possible allergens, such as nickel. We note that the biocompatibility is dependent upon how a device is integrated. For example, an on-skin device only needs to be skin-compatible [94], whereas devices that are implanted [28] or ingested [41] must meet higher requirements to avoid immune system responses. When non-biocompatible materials cannot be avoided, sealing the device is an option; these seals, however, must be robust enough under high mechanical and chemical stress to avoid leakages or compromising the user's body.

Miniaturization: Despite the impressive miniaturization of electronics in recent years, most wearable devices are still too large to be integrated into our bodies. Recent work with on-skin electronics shows that thin touch sensors (4–46um) [95] permit the use of small body landmarks. These enable the use of the body's geometry for input [95] or to help in recalling virtual elements [8]. Similarly, devices that are implanted require also a very small form factor to be worn comfortably under the skin. In addition to input and output surfaces, such integration requires much smaller processing units, batteries, energy harvesters, and antennas.

Deformability: We believe that integrated devices should be deformable, for example, flexible, compliant, and stretchable. First, compliance allow for robust devices that are better in absorbing shocks and damage. Second, flexibility and compliance are important to ensure a good fit to the curved and flexible human body.

Tailored Technologies for the Body

We find that integrated devices should support the wide range of shapes and sizes of the human body [17, 99]. For example, body sensors need to be automatically calibrated for each individual to allow for continuous usage as examplified in the work by Knibbe et al. [38]. Hence, a "made to measure" approach for technologies is required. Beyond size and shape differences, body decorations have a long tradition in many cultures [16]. Therefore, visual customization and aesthetic electronics could increase the acceptability of such devices. Early examples are interactive beauty products [90] and visual aesthetic on-skin devices [94, 33, 44].

We note that personalized devices are a stark contrast to today's mass-fabrication of technologies, which excels in producing identical devices in high quantities at a low cost, but which cannot be easily customized. A potential solution is end-user customization (e.g., cuttable electronics [60]), which enables the mass-fabrication of a single form-factor that allows for subsequent adaptations by the end-user. An alternative could be the use of single-unit fabrication methods (e.g., printed electronics [79] and 3D printing [49]). These technologies create highly personalized devices, but are currently slower and more expensive than traditional mass-fabrication methods. Beyond the fabrication step, it is important to consider the whole design process, which requires easy ways to gather the geometric information from the body and novel CAD software (as shown, for example, for multi-touch surfaces [58]) for the end-user that translates geometric shapes and visual designs into functional devices.

Connecting the Integrated Body with Additional Devices

Integrated technologies will often require communication between the interactive device and devices on the internet or around the user's body (e.g., to store and backup data, etc.). Different methods have already been proposed to form such body area networks [12], but miniaturization, data transfer, and energy consumption are still an open challenge. With the event of connectivity, integrated devices also require high standards of security to prevent malicious digital attacks on the user's body.

In particular, we find that energy management is an interesting domain for integrated devices. They can be either charged through an epidermal port, wirelessly [28, 84], or harvest energy from the body [71]. Energy harvesting could be the most useful form for integrated devices since they do not require manual charging, but rather take the required energy from the human body. However, most current methods generate too small amounts of power for today's electronic systems.

CHALLENGE #2: EFFECTS ON IDENTITY AND BEHAVIOR

We now describe the challenge concerning identity and behavior around HInt systems. We previously described the technologies that one might use to create a new integrated self (e.g., user that is integrated with a particular interface); however, a new integrated self comes with a possible shift in the perception of self. Furthermore, this integrated self will most likely be also perceived differently by the surrounding people, whether they are other integrated selves or selves without these types of interface augmentation. This creates a perceptual feedback loop between the integrated self and the interactions with others as human beings are influenced by how they are perceived by others. Addressing these challenges will produce empirical and theoretical insights about who we are and who we want to become [56] within a future where integrated and non-integrated selves interact with each other.

Perception of the Integrated Self

The relational self is the part of an individual's self-concept, which consists of the feelings and beliefs that one has regarding oneself and develops based on interactions with others [4]. Self-perception is thus said to be created through information from different sources and modalities. While the majority of interfaces mostly addressed the visual and auditory senses, as we described, HInt systems tend to operate at a physical level that involves other bodily senses, such as proprioception, etc. Therefore, we believe that the usage of a larger multisensory stimulation in HInt systems might have a significant impact on the relational self [59, 77, 91].

Furthermore, one's self-image can be modified through technology by either changing the perception of ourselves or by physically changing ourselves. As an example, Riva et al. [66] and Nishida et al. [57] demonstrated that one's body schema can be changed by simply seeing a different body to their own through a head mounted display. Furthermore, technology has the potential to enhance our sensory system, for example, by extending the abilities of the visual sensation through wearing thermal imaging glasses [1] or by a brain-computer interface that allows accessing other people's indicated cognitive load [26].

Lastly, the perception of self implies a social loop in which we react to others' reactions on us. Thus, we now describe a possible lens of analysis from the opposite perspective, the perception of other integrated selves.

Perception of other Integrated Selves

Social groups are built around individuals to which they belong to various extents. This is often based on a relation between individual attributes and a social expectation set of accepted or denied status symbols and a set of behavior rules that the group commonly agrees on [88]. If an individual has more attributes with a high social acceptance, it is more likely that their role within the group is a leadership position. Interestingly, an attribute, such as a perceived strength of an integrated self that is positively perceived in one individual can cause a negative perception in another as the relationship to individuals biases our emotions toward individuals positively or negatively [15]. *What does this mean for HInt?* Let us envision interacting with an individual using HInt technology that might be able to, for example, see through their augmented vision when we become nervous or they might – while conversing with us – be able to access past conversations (e.g., Mann's AR interface [50]). Such ability extends their previous non-integrated self, and other selves will, according to Cuddy [15], appreciate the increase of the integrated self's abilities if they are a friend and belong to their social group. We might see this HInt-individual as a positive addition to their group as their increased abilities ultimately improve the group. However, if the individual is seen as a competitor or might not not belong to our social circle, we may not want to let that person know when we, for example, are insecure or nervous as that information could bring our competitor into a better position. Consequently, the ability of the integrated self will be perceived as an increase of competition and may even be disliked, arouse envy or even create mistrust.

Besides the effect of emotions towards HInt users caused by the relationship between user and others, some technologies might be more critically perceived than others, especially when a technology fails to respect personal or privacy rights (e.g., cameras or microphones that eavesdrop on conversations). For example, we may wish to be informed if a device in our surroundings is switched on or off, or what data is being recorded for what purpose and by whom. Furthermore, the HInt user also faces challenges as bystanders may develop mistrust and act differently or distanced. Hence, it is beneficial that the HInt technology provides transparency in its interface [40].

Moreover, we believe that designers of HInt systems should take into account its context of application and the ownership of its benefits. For example, bystanders are often more open to accept integrated selves if the technology enables the user to have skills that others commonly have, e.g., the acceptance of cameras that empower visually impaired people is higher compared to the acceptance of cameras of users who have no visual impairment [39].

Evaluating Potential Issues of the Self

When we integrate technology with ourselves, how do we evaluate the effects in regards to the self? Questionnaires could help in evaluating effects of the perception of oneself or of others. For example, Schwind et al. [72] investigated the acceptance of VR technology in different social setups through modifying the questionnaire from Profita et al. [63]. Moreover, qualitative approaches could also be beneficial. For example, psycho-phenomenology can provide a relevant lens into human subjective experiences, which could be useful here. One specific method is the explicitation interview technique [52], which is a form of guided introspection that seeks first-person accounts by using distinctions in language, internal sensory representations, and imagery. The value of this interview technique lies in the way of asking questions that supports participants in expressing their experiences linked to a specific moment. For example, the interviewer asks questions like "Please describe what you feel, see, hear, or perceive" and follows up with questions that help to place the participant in an evocation state so they talk about that specific lived experience (including action, sensory perception, thoughts, and emotions) in all its details rather then focusing on conceptual, imaginary, and symbolic verbalizations, such as theories, rules, or knowledge.

Similarly, Koelle et al. [40] demonstrated a participatory design approach to develop devices that take into account such issues, which we believe would be useful to consider when aiming to evaluate issues of the self. The design challenges that the authors explicitly focused on were the user experience of smart cams, which bystanders do not feel comfortable with. Their approach starts with (1) development while highlighting social acceptance challenges; (2) involve experts from multiple relevant disciplines to create a set of prototypes; (3) analyze the prototypes to aggregate design strategies; (4) and evaluate the design strategies with UX experts to (5) define solutions that incorporate product requirements, such as social acceptability, interface transparency, and interfaces that not only please the user but also respect the bystander.

CHALLENGE #3: INTEGRATION AND SOCIETY

Current and future HInt devices will affect society in a variety of ways. Designers, researchers, industry, and regulatory bodies will need to attend to these. While we believe the process of developing new products, services, and regulations should be democratic, informed, inclusive, and involve public dialogues, in this paper, we do not take a strong stance on a specific ethical principle, but rather present a list of key societal challenges.

Digital Divide

Previous interactive technologies, such as interactive devices with internet access have led to concerns about inequality in access, often referred to as the "digital divide". We see this being potentially amplified as devices are becoming integrated. When technologies are augmenting senses or giving people new capabilities, new divides will be created which may have new and unexpected consequences. For example, if areas of public space are designed for people with new sensory capabilities, does the sensory-divide created by this design exclude people who cannot afford the augmentation? We can already see how new technologies affect public space with, for example, the decline in publicly visible clocks as mobile phones with time information became widespread [53]. If, for example, new visual capabilities remove the need for navigation and information systems, public maps and signs might be removed; the result would be a world that is profoundly disabling for humans without access to these systems.

Body Bias

We believe that direct fusions interfacing with the user's body might also lead to an increase in "body bias". Integrated systems are inherently more dependent on the nature of the body they are fusing with, for example, some biosensors function differently on skins of different ethnicities [93]. More basically, variability in body shape and size may increasingly become a factor as we fuse technology with the body. Differences relating to gender and age may also affect how people are able to interact with their integrated bodies. We note that this challenge is also a software one: as we design software systems to integrate with a person's body, we need to consider the potential for such designs to embed assumptions of cultural, gender, or physical differences.

Mental and Physical Health

As with all technologies that form a long-term part of people's lives, such as the car or the smartphone, there is also a potential for negative impact on mental and physical health, for example see the impact of the aforementioned technologies on increased poor posture, greater stress levels, and heightened risk levels due to the distractions they afford.

Ownership and Accountability

Business models of companies such as social networking software providers aim to create a range of dependencies in users that ensure the continued use of the systems and ultimately drive profit. We find that, as systems become more integrated, this increasingly creates a range of challenges for users, developers, and regulators. When our body is part of a combined ecosystem of devices, which may exhibit a level of agency, we need to understand what the different motivations of the different systems are (e.g., *"Is the system providing a service in return for advertising to the user?"*) and develop ways for attributing responsibility for the actions of the combined system (*"Who is at fault if my exoskeleton makes me harm someone; me or the software developer who programmed the exoskeleton wrongly?"*). We also need to consider ongoing maintenance and support. Many modern hardware systems are highly dependent upon the continued running of cloud services, which blurs the nature of the ownership of the devices, even if any physical device belongs to a user. As devices are increasingly integrated and users become reliant on them, we must consider what the effect on users is at the point when devices become unsupported. In the case of in-body devices, regulation may even be required to enable ongoing support and maintenance by third parties in the event of the failure of the company.

CHALLENGE #4: DESIGNING INTEGRATED INTERACTION

This section describes the challenges HInt poses for interaction design. HInt has two key qualities which are relevant to design: (1) the system can exhibit a form of autonomy that needs to be coordinated with the user and (2) the system's real-time feedback fuses with the user's sensations. HInt systems are therefore uniquely challenging in their integration of autonomy and real-time feedback. In response, we have identified three key design challenges: applying novel technologies, designing implicit interactions, and designing for variable agency.

Integrating Novel Technologies

One of the key challenges for HInt is to develop common understandings and tools for designing, developing, refining, testing, and evaluating HInt systems, especially as many HInt systems contain novel technologies that afford new types of interaction. Thus, novel technologies are like new materials which require careful characterisation and profiling. Many of these interface advances draw on disciplines – e.g. physiology, chemistry, neurophysiology – that are relatively new to HCI. It might therefore be desirable to develop toolkits for these technologies to make them easier for designers to apply to new applications.

Designing Implicit Interaction

Unlike the application and integration issues that stem from the migration of HCI technologies to the bodily domain, the interaction issues that stem from operating just beneath or just above the user's awareness as well as just ahead or just behind the user's intent, have little direct precedent in the space of medical devices or even prosthetics [32, 73]. Therefore, we believe that integrated systems would benefit from knowledge of how tightly coupled performers operate, like dance partners.

Designing for Variable Agency

We find that a HInt system is often experienced in various ways based on how its control is distributed to its users. For example, it might be designed in such a way that the technology acts as an extension of the body while displaying minimal or no autonomous behavior at which one can interact in a reflexive manner [51]. Many systems offload cognitive or motor effort away from users and instead automate technology. As systems shift from explicit control to autonomous (e.g., from driving the car to having the car drive itself), the interaction gradually shifts from a singular entity exploring the world through technology (e.g., driving the car) to an agent-like system that explores the world by itself (e.g., a self-driving car). As such, from a phenomenological perspective, HInt systems might therefore feel like an extra limb, either natural to use, such as the extra hand holding your bag when you need to rummage through it or with its own agency, like an EMS-controlled arm [45] that acts of its own intent.

Therefore, the key challenge for the designer is to determine what parts of the system should be provided with agency and to what extent. Furthermore, increasing a person's agency in this context also presents a low level challenge for the designer. For example, how does one design a technology that truly provides the experience of *"I did that"* rather than *"The tool did that for me"*? Intentional binding provides us with a tool from neuroscience for evaluating these phenomenas quantitatively [14, 9]. However, we find that the design space is not yet well understood as more and more interfaces find new configurations for shared agency [34]. A design framework might therefore be useful to guide designers regarding both, where and how to endow a system with agency.

Perceptual Transparency

When perceiving information, we have different strategies available for interpreting it. For example, information might be mediated symbolically and require an interpretive step from the user. If, for instance, checking the weather in an app, we are provided with a number that represents the outside temperature. We then cross-reference this with our lived experiences and infer what it might feel like. Due to this interpretive step, such mediation of information is referred to as "hermeneutic" [30, 92]. Hermeneutic mediation is often juxtaposed with embodied mediation [92]. The canonical example of embodied mediation is perceiving the world through a cane. A more technologically sophisticated example might be a haptic teleoperation system, which directly provides the target sensation [62]. Rather than demanding the interpretive step described before, embodied mediation allows reflecting on one's current state of being to understand the information. It is this latter, a more direct way of understanding, which we wish to be achieved with HInt systems. We see this direct transfer of sensations between the user and the device as a type of "perceptual transparency" that can be achieved in two possible ways:

Transparency through sensory access

In the context of haptic teleoperation, a system is said to be transparent "if the human operator feels as if they are interacting directly with the environment" [61]. Virtual reality is able to visually transport users to remote or imaginary places by providing users with the necessary visual cues. However, for other senses, this is less trivial, leading designers to often use proxy symbols (e.g., green clouds for bad smell, vibration for object collisions). To avoid such proxy symbols, we must understand that perception is an activity that the body performs. By acting in the world, the body changes the sensory information it is exposed to, which in turn triggers new actions [2]. Injecting information into such interactions enables the presentation of artificial sensory experiences, for example providing the experience of texture where there is none [67] or sensations such as resistance and weight [83]. While examples of systems that support embodied mediation of information exist, they are typically limited to a particular sensory modality or to specific information. Creating systems without such constraints requires a generalized approach of achieving sensory transparency for all our senses and is thus open challenge.

Transparency through understanding other minds

People already have an embodied understanding of others through our shared experience of having a body. People assume their one movements to be equivalent to the movements of others [11]. These experiences need not be in perfect sensorial agreement for a set of individuals to interact, e.g., a sheep dog, sheep, and a shepherd can act in unison, even though they perceive the situation radically different by means of their senses [35]. We find that the tool set we have at our disposal for understanding others is currently poorly suited for inferring motivations of others, whether they are humans or interfaces for interactive devices. Conversely, such agents behind interactive devices often only have very sparse information of their user and the world around them, paired with simplistic resources for interpreting these. However, even simple information, such as body temperature or step count, change their meaning based on the user's context. We find that providing interfaces with access to other's, for example, mental states, goals, and motivations [54], ranging from raw data to actionable information [55], is a non-trivial process. As such, the challenge becomes how to design interfaces so that we can intuitively asses their motivations and goals and how to provide these with the tools they need to understand us in a way that supports a partnership.

CONCLUSION

In conclusion, we find that the field of human-computer integration (Hint) is rapidly expanding, embracing new technologies, and incorporating new disciplines. At the same time, the field is beginning to converge on key questions, surrounding technology, self-perception, societal, and design implications, which we identified in this paper.

We discussed what we consider to be the key set of challenges the field currently faces. These challenges emerged from a workshop with 29 experts. The challenges will evolve as technology advances, society changes, design knowledge improves, and our self-understanding increases. Many HInt systems already exist and offer engaging experiences. However, we believe the challenges we identified need to be addressed in order to reap the full benefits of a HInt future.

Our hope is that designers venturing into human-computer integration will use this work to become aware of the challenges they will face. Moreover, those deep in the field (who might already know many of these next steps and challenges) will also benefit as the work will provide them with an initial vocabulary to describe their experiences. Similarly, we expect that theorists will also benefit from our work as they can use it to verify their theories regarding real-world practice or to help answer some of the immediate challenges. Developers can also use our work to identify opportunities for innovation by looking at specific implementation challenges. Finally, educators can also benefit from this work by looking at the challenges to identify future research topics.

It is important that one also recognizes the limitations of the HInt field. In research on proxemics, researchers have identified "Dark Patterns" [25], which are application scenarios where users are deliberately deceived through a particular interaction technology. We can envision that similar scenarios might occur within the HInt field, and therefore we encourage future work to conduct such investigations, while hoping that our work can be useful to structure such investigations.

We acknowledge that our approach of conducting a workshop with 29 experts has not only advantages, but also disadvantages, for example our experts are eager to drive this field forward, as such might be optimistic about broader social acceptability. However, we believe our workshop format is also a unique approach when it comes to compiling key challenges for HInt that goes beyond one individual's own work. As such, we see the identified challenges not necessarily as problems that need fixing, but rather aspects that need more examination and research. Therefore, we believe that our challenges are only a starting point that needs to be developed and critiqued further by others, including theorists and designers.

In summary, we are excited about the potential of the HInt field and how it will affect how users engage with technology. With the articulation of our set of challenges, we hope we will motivate further research efforts towards this exciting future. Ultimately, with our work, we want to support you in contributing to the future of human-computer integration.

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