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SURVEY ARTICLE

Seven HCI Grand Challenges

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ABSTRACT
This article aims to investigate the Grand Challenges which arise in the current and emerging landscape of rapid technological evolution towards more intelligent interactive technologies, coupled with increased and widened societal needs, as well as individual and collective expectations that HCI, as a discipline, is called upon to address. A perspective oriented to humane and social values is adopted, formulating the challenges in terms of the impact of emerging intelligent interactive technologies on human life both at the individual and societal levels. Seven Grand Challenges are identified and presented in this article: Human-Technology Symbiosis; Human-Environment Interactions; Ethics, Privacy and Security; Well-being, Health and Eudaimonia; Accessibility and Universal Access; Learning and Creativity; and Social Organization and Democracy. Although not exhaustive, they summarize the views and research priorities of an international interdisciplinary group of experts, reflecting different scientific perspectives, methodological approaches and application domains. Each identified Grand Challenge is analyzed in terms of: concept and problem definition; main research issues involved and state of the art; and associated emerging requirements.

BACKGROUND
This article presents the results of the collective effort of a group of 32 experts involved in the community of the Human Computer Interaction International (HCII) Conference series. The group's collaboration started in early 2018 with the collection of opinions from all group members, each asked to independently list and describe five HCI grand challenges. During a one-day meeting held on the 20th July 2018 in the context of the HCI International 2018 Conference in Las Vegas, USA, the identified topics were debated and challenges were formulated in terms of the impact of emerging intelligent interactive technologies on human life both at the individual and societal levels. Further analysis and consolidation led to a set of seven Grand Challenges presented herein. This activity was organized and supported by the HCII Conference series.

1. Introduction

In the current wave of technological evolution, a near future is foreseen where technology is omnipresent, machines predict and anticipate human needs, robotic systems are an integral part of everyday life, and humans' abilities are technologically supported. Home, work, and public environments are anticipated to be smart, anticipating and adapting to the needs of their inhabitants and visitors, empowered with Artificial Intelligence (AI) and employing big data towards training and perfecting their reasoning. Interactions in such environments will be not only conscious and intentional, but also subconscious and even

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unintentional. Users' location, postures, emotions, habits, intentions, culture and thoughts can all constitute candidate input commands to a variety of visible and invisible technological artifacts embedded in the environment. Robotics and autonomous agents will be typically embedded in such technologically enriched environments. Information will be communicated from one interaction counterpart to another 'naturally', while the digital world will coexist with and augment physical reality, resulting in hybrid worlds.

The focus of HCI has traditionally been the human and how to ensure that technology serves users' needs in the best possible way, a perspective that is claimed to – and so it should – constitute also the ultimate goal of the new intelligent technological realm. HCI has evolved over the years, has considerably enlarged its domain of enquiry, and has achieved remarkable advances. However, as new technologies bring increased complexity and escalate the need for interaction and communication in numerous ways, the human counterpart of technology is also changing, becoming more conscious of the impact that interactive systems and devices have on everyday life: humans have become more attentive and demanding, yet also appear to be less optimistic, as well as more concerned and critical. As a consequence, human-centered approaches have to face new challenges, calling for shifts in both focus and methods, in order to formulate and address the critical issues that underlie a more trustful and beneficial relationship between humankind and technology.

In recent years, many proposals have been put forward regarding the future of HCI and its renewed research agenda. Norman (2007) in his book "The Design of Future Things" reshaped the concepts and methods of product design under the light of the freshly emerging dilemma of automation *vs*. control and machine intelligence *vs*. human intelligence. Ten years later, as artificial intelligence began demonstrating practical feasibility and impact, following a number of rise and fall cycles, Kaplan (2016) in "Artificial Intelligence: Think Again" strives to clarify common misunderstandings and myths around machine intelligence, bringing back the issue to one of sensible design which accommodates social, cultural, and ethical conventions.

With respect to societal aspects of HCI research, Hochheiser and Lazar (2007) in "HCI and Societal Issues: A Framework for Engagement", define the factors and mechanisms which underlie HCI responses to societal demands and call for proactive and principled engagement in design. Along these lines, Value Sensitive Design uses explicit consideration of specific values as a means of achieving goals – such as democracy, fairness, inclusion, and appropriate use of technology – by addressing questions such as: which values are important in a given design case; whose values are they and how are they defined with respect to the given context; which methods are suited to discover, elicit and define values; what kind of social science knowledge or skills are needed; *etc*. (Friedman, Kahn, Borning, & Huldtgren, 2013).

In the first decade of the new millennium, by seeking to address human value in the development of intelligent interaction, Harper, Rodden, Rogers, and Sellen (2008) reflect upon ongoing changes and outline a new paradigm for understanding human relationship with technology, whereby the boundaries between computers and people, and between computers and the physical world are reconsidered, also taking into account increasing techno-dependency, collection of digital footprints and increasing creative engagement. In such a context, HCI needs to develop new views about the role, function, and consequences of design, form new partnerships with other disciplines, and re-examine and reflect on its basic terms and concepts.

Also, Shneiderman et al. (2016), in their article "Grand Challenges for HCI Researchers" analyze the role of HCI in addressing important societal challenges, identify 16 grand challenges related to both society-oriented and technology-oriented issues, and highlight the need for improved interdisciplinary methods that emerge from science, engineering, and design.

This article presents the results of the collective effort of a group of 32 experts involved in the community of the Human Computer Interaction International (HCII) Conference series. The goal is to investigate the grand challenges which arise in the current landscape of rapid technological evolution towards more intelligent interactive technologies, coupled with increased and widened societal needs, as well as individual and collective expectations that HCI, as a discipline, is called upon to address.

The group's collaboration started in early 2018 with the collection of opinions from all group members, each asked by email to independently list and describe five challenges of greatest importance to their area. The expressed opinions were collected and classified into 10 categories which were summarized in a draft document. During a one-day meeting held on the 20th July 2018 in the context of the HCI International 2018 Conference in Las Vegas, USA, the identified items were analyzed and discussed, and a condensed set of challenges was produced. The group took the decision to formulate the challenges in terms of the impact of emerging interactive technologies on human life, both at the individual and societal levels. Further consolidation led to a set of seven challenges, as depicted in Figure 1. A definition and the rationale behind each challenge is presented in Table 1. It should be noted that challenges are not presented in a hierarchical manner, nor in order of importance; all the identified challenges are considered equally important in the context of future technological environments. It is also inevitable that the discussions that follow are interconnected, involving issues that are common in more than one challenges. For example, privacy and ethics are a major concern for human-technology symbiosis, e-health services, and technology-supported learning activities, therefore although they are discussed in detail in Section 4 (Ethics, Privacy, and Security), they are also briefly introduced in other sections as well. To the extent possible, redirections to relevant discussions within the paper are provided.

Whereas some of the identified challenges are common to the previous approaches – similar to those suggested by earlier efforts as published in the articles mentioned above, thus confirming their perceived importance and urgency among the scientific community, this paper engages a larger group of experts in the field – from various sub-disciplines in HCI, who also discussed and debated the addressed issues at a greater depth. Further, this group of experts not only identified the challenges but also has attempted to analyze at a deeper level the current debate around each challenge and to propose a rather detailed list of related research topics for each challenge in a systematic manner. Thus, this paper advances the discussions on the future of HCI research and contributes to the development of current and future HCI research.

Figure 1. The Seven Grand Challenges.

The effort was motivated by the "intelligence" and the smart features that already exist in current technologies (*e.g.* smartphone applications monitoring activity and offering tips for a more active and healthy lifestyle, cookies recording web transactions in order to produce personalized experiences) and that can be embedded in future environments we will live in. Yet, the perspective adopted is profoundly human-centered, bringing to the foreground issues that should be further elaborated to achieve a human-centered approach – catering for meaningful human control, human safety and ethics – in support of humans' health and well-being, learning and creativity, as well as social organization and democracy.

In the subsequent sections of this article, each identified challenge is analyzed in terms of concepts and problem definition, main research issues involved and state of the art, as well as the associated emerging requirements, with the ultimate goal of offering to the HCI community food for thought and inspiration towards identifying and addressing compelling topics for investigation and lines of research.

2. Human-technology symbiosis

2.1. Definitions and rationale

Many drops of sci-fi ink have been devoted to describing futures in which technology is ubiquitous and integrated in everyday objects, holograms and robots are typical interaction counterparts, humans live in virtual worlds, and often they are technologically augmented. Although featured in sci-fi novels and movies, some of the above technological advances are already a reality, while others are soon expected to permeate society. There is already a trend that everything must be 'smart', whether it is a device, software, service, car, environment, or even an entire city. Technological advancements will eventually make it possible to inject some AI into even the most common products, a revolution occurring so gradually that it may have passed unnoticed (Holmquist, 2017). The advent of smart ecosystems, comprising smart devices, services, materials, and environments that cooperate in a seamless and invisible manner, imposes the need for considering, defining, and optimizing the terms of symbiosis of the two main counterparts, namely humans and technology.

Several terms in the HCI literature have been introduced to reflect how humans experience the new Information and Communication Technology (ICT) era, including Human-Computer Confluence and Human-Computer Integration. Human-Computer Confluence describes a research area studying how the emerging symbiotic relations between humans and ICT can be based on radically new forms of sensing, perception, interaction, and understanding (Ferscha, 2016). Human-Computer Integration broadly refers to the partnership or symbiotic relationship in which humans and software act with autonomy, giving rise to patterns of behavior that must be considered holistically (Farooq & Grudin, 2016). Human-Computer Symbiosis was introduced by Licklider back in 1960, who envisioned a future when human brains and computing machines – tightly coupled together – would "think as no human brain has ever thought and process data in a way not approached by the information-handling machines we know today" (Licklider, 1960, *p.* 1)

Table 1. Definition and rationale for each identified challenge.

Human-Technology Symbiosis

Definition: Human-technology symbiosis refers to defining how humans will live and work harmoniously together with technology, which in the near future will exhibit characteristics that until now were typically associated with human behavior and intelligence, namely understanding language, learning, reasoning, and problem solving (keeping in mind that they are limited to specific application domains).

Rationale: The advent of smart ecosystems, comprising smart devices, services, materials, and environments that cooperate in a seamless and transparent manner, imposes the need for considering, defining, and optimizing the terms of symbiosis of the two main counterparts, namely humans and technology.

Human-Environment Interactions

Definition: Human-environment interactions refer to the interaction of people not only with a single artifact, but with entire technological ecosystems featuring increased interactivity and intelligence.

Rationale: In technologically enriched, autonomous, and smart environments, interactions will become more implicit, often concealed in the continuum between the physical and the digital. Therefore, the topic of supporting human interactions in these environments brings about novel implications and challenges.

Ethics, Privacy and Security

Definition: Ethics refer to moral principles that govern behavior. In this paper, it refers to the moral principles that govern the conduct of activities in the context of HCI, and in particular design. Privacy refers to the ability of users to be in control and to determine what data can be collected and exploited by a computer system and then be shared with third parties. Security in the context of computing refers to the protection of computer systems from theft or damage to their hardware, software or electronic data, as well as from disruption or misdirection of the services they provide.

Rationale: Intelligent systems need to behave so that they are beneficial to people beyond simply reaching functional goals or addressing technical problems, by serving human rights and the values of their users, ensuring privacy and cybersecurity. Ethics, privacy, trust and security have always been important concerns in relation to technology, acquiring yet new dimensions in the context of technologically augmented and intelligent environments.

Well-being, Health and Eudaimonia

Definition: Health refers to a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. Well-being also includes achieving high life satisfaction, happiness, prosperity, and a sense of meaning or purpose. Eudaimonia refers to a person's state of excellence characterized by objective flourishing across a lifetime, and brought about through the exercise of moral virtue, practical wisdom, and rationality.

Rationale: Technological advances, coupled with advances in medicine, offer the opportunity to provide more effective and less expensive ways of fostering a healthy life. Beyond physical health, technology can also be used to promote human well-being, including not only health aspects, but also psychological well-being through life goals' fulfilment (eudaimonia). Overall, technology in the context of healthcare is already widely used, yet there are still open research issues. Moreover, in a world where technology is omnipresent, the question arises of how its role towards enhancing well-being and human eudaimonia can be optimized, especially addressing interaction issues and ensuring a human-centered approach.

Accessibility and Universal Access

Definition: Accessibility refers to the design of products, devices, services, or environments suitable for people with disabilities. Universal Access refers to the accessibility and usability of Information Society Technologies by anyone, anywhere, anytime.

Rationale: Intelligent environments bring new challenges regarding accessibility and universal access, mainly stemming from the increased technological complexity, having considerable impact on the access not only to information or technology, but to a wide variety of services and activities of daily life. As HCI has always focused on the human, in the new technology-augmented environments, efforts in the field will be extended towards improving the quality of life of various populations, including the disabled and older persons. Accessibility and Universal Access are not new concepts, however in view of the demographic development (aging society) and of the constantly increasing technological complexity, they become not only timely, but also pivotal for the prosperity of future societies.

Learning and Creativity

Definition: Learning refers to the activity or process of gaining knowledge or skill by studying, practicing, being taught, or experiencing something. Creativity refers to the ability to produce original and unusual ideas, or to make something new or imaginative.

Rationale: As technologies continue to mature, new opportunities for fostering individual growth through multimodal stimulation of how humans learn and apply creativity will emerge; people with diverse backgrounds, skills, and interests will be able to collaborate to solve challenging problems, by cooperatively learning and creating knowledge together. New technologies have the potential to support new and emerging learning styles, as they have recently evolved and been influenced by the pervasiveness of technology in the everyday life of the new generations. At the same time, the discussion of how technology should be applied in the learning context has become timelier than ever, expanding to issues such as privacy and ethics, learning theories and models, and pedagogical aspects. In any case, the success of technology in education depends to a large extent on HCI issues. On the other hand, human creativity is expected to have a central role in the future society, therefore, it is important to not only cultivate it, but also explore how it can be assisted.

Social Organization and Democracy

Definition: Social organization refers to the formation of a stable structure of relations inside a group, which provides a basis for smooth functioning of the group. Democracy refers to a form of government in which the people freely govern themselves and where the executive (or administrative) and law-making (or legislative) power is given to persons elected by the population.

Rationale: As humanity moves from smart environments towards smart societies where an abundance of ethical concerns arise, social organization should be supported. HCI research will have a multifaceted pivotal role in the forthcoming technological developments, addressing major societal and environmental challenges towards societies where the ideals of democracy, equality, prosperity, and stability are pursued and safeguarded. The critical times we live in, as well as future dark scenarios, have already directed research towards creating technology to assist humanity in coping with major problems, such as resource scarcity, climate change, poverty and disasters. Social participation, social justice, and democracy are ideals that should not only be desired in this context, but also actively and systematically pursued and achieved.

Symbiosis – a term mentioned in all the aforementioned approaches – is a composite Greek word meaning "to live together". Emphasizing not only on "together" but also on "living", symbiosis is an ideal term to use when discussing the challenges stemming from the co-existence and interactions of two counterparts: humankind and intelligent computer systems that exhibit characteristics, which until now were typically associated with human behavior and intelligence, namely understanding language, learning, reasoning, and problem solving (Cohen & Feigenbaum, 2014). At the same time, one has to be aware that the results refer only to specific domains. This section discusses the challenges of this symbiosis, with a focus on supporting and empowering humans, ensuring at the same time human control and safety.

2.2. Main research issues and state of the art

2.2.1. Meaningful human control

A major concern is that, despite the "intelligence" of the technology and its potential to make automatic inferences and decisions, humans should be kept in the loop through supervisory control and monitoring of intelligent autonomous systems. A representative example of human control over automated systems, is that of pilots who have a supervisory control of systems and flight deck. The pilots exercise control in an outer-loop manner (setting high-level goals and monitoring systems), rather than in an inner loop manner ('hands on', minute to minute). This has changed dramatically the nature of the pilot's control task on the flight deck. A similar design problem, relevant for a much larger population of users, arises with the advent and diffusion of automated driving at levels which are not fully automated. Here, the issue of design trade-offs between human control and automation has to be addressed in terms of transferring control between driver and vehicle (forth and back when switching between autonomy levels).

Meaningful human control has been defined as one of the short-term research priorities for robust and beneficial AI, whether it is through human in the loop, on the loop, or some other protocol (Russell, Dewey, & Tegmark, 2015). The various protocols refer to how human interference affects acting entities (*e.g.* an AI agent); for example, when human interference directly affects the acting entity it is referred as "human in the loop", while when it indirectly affects the actions or the community of the entity it is referred as "human on the loop" (Hexmoor, McLaughlan, & Tuli, 2009). In any case, meaningful human control is a principle that goes beyond any specific protocol; it advocates that humans, not computers and their algorithms, should ultimately remain in control of – and thus be morally responsible for – actions mediated by autonomous systems (Chen & Barnes, 2014; Santoni de Sio & van Den Hoven, 2018).

To achieve human control, important features of intelligent systems are transparency, understandability and accountability, which also contribute towards building a relationship of trust between the user and the system and boost the performance of the human-automation team (Chen et al., 2018; Pynadath, Barnes, Wang, & Chen, 2018; Siau & Wang, 2018). In particular, transparent user interfaces make their own decisions and outcomes visible, clarify users' responsibility, and can promote more appropriate behaviors (Chen et al., 2018; Shneiderman et al., 2016). Transparency is closely related to system interpretability/explainability, a property of machine learning systems indicating their ability to explain and present information in a manner understandable by humans (Došilović, Brčić, & Hlupić, 2018). Benefits of explainable AI include the capability for verification and improvement of the system, compliance with legislation, as well as the potential for human learning and acquisition of new insights (Samek, Wiegand, & Müller, 2017). On the other hand, the ideal of complex systems' transparency faces technical and temporal limitations, as well as major shortcomings (Ananny & Crawford, 2018). For instance, transparency can lose its power if it does not have meaningful effects, while it can also create privacy threats. More importantly, making a system visible does not necessarily mean that it is understandable, which is a truly challenging task when it comes to complex systems. In this respect, transparency also entails accessibility concerns, in terms of providing appropriate explanations in a comprehensible manner (see also Section 5.2.3).

Besides transparency, understandability is fostered by intelligibility and accountability, which allows users to better understand underlying computational processes, and therefore gives them the potential to control system actions better (Shneiderman et al., 2016). Intelligibility can be defined as the answer to the question "how does this work?", while accountability as the answer to the question "who is responsible for the way it works?" (Floridi et al., 2018). Assuming that people have decided to provide personal data in order to use a smart service (see also Section 4), it is an important challenge to keep people in the loop and in control so as to determine how the service is provided and under which conditions. Other challenges related to making intelligent systems understandable to users refer to these systems' inherent opacity and unpredictability. Systems featuring AI will have the ability to evolve themselves without human influence in a way that is not explicit, even to their developers, drawing their own conclusions from given data. This can result in systems behaving in a manner that is not predictable, a feature that must be effectively communicated to users, so as to avoid jeopardizing their trust and confidence in the system (Chen et al., 2018; Holmquist, 2017). One could even argue that – depending on the application domain – such an unpredictable and opaque as well as independent/autonomous behavior should be prohibited, *e.g.*, in safety-critical situations, where the implications are devastating.

2.2.2. Humane digital intelligence

The above issues point toward the bigger picture of a humane digital intelligence, which does not merely incorporate human values in the innovation process, but actually brings them to the forefront, emphasizing people and their experience with technology, not just 'intelligent functionality' and 'intuitive usability' (Bibri, 2015). The key criteria for technology adoption will move away from technical or User Experience (UX) issues towards how aligned technology is with human values (José, Rodrigues, & Otero, 2010).

Therefore, smart should stand for "smart, but only if cooperative and humane" (Streitz, 2018). In brief, the humane face of intelligence (Tegmark, 2017) entails the establishment of a calm technology (Weiser, 1991) supporting and respecting individual and social life, the respect for human rights and privacy, supporting humans in their activities, pursuing trust, as well as enabling humans to exploit their individual, creative, social and economic potential, and to live and enjoy a self-determined life (Streitz, 2017).

2.2.3. Adaptation and personalization to human needs

In the same context, intelligent environments should be able to think and behave in ways that support humans, by providing personalized, adaptive, responsive, and proactive services in a variety of settings: living spaces, work spaces, social and public places, and on the move (Bibri, 2015). Such a behavior constitutes a fundamental characteristic of Ambient Intelligence (AmI) environments, as they were initially introduced in 2001, through the elaboration of the IST Advisory Group (ISTAG) Ambient Intelligence scenarios in the near future of 2010 (Ducatel, Bogdanowicz, Scapolo, Leijten, & Burgelman, 2001). The AmI approach already adopted at that time an orientation towards the goals and values which are discussed now again in the scientific community and also reflected in this paper.

To support the vision of personalized, adaptive, responsive, and proactive services, adaptation and personalization methods and techniques will need to consider how to incorporate AI and big data (Siau & Wang, 2018). These technologies are expected to work in synergy in intelligent environments, as deep learning algorithms need comparatively big data to learn sufficient knowledge from it and perfect their decision-making (Lan et al., 2018). Meanwhile, AI has already been used in several different ways to facilitate capturing and structuring big data, and to analyze big data for key insights (O'Leary, 2013; Siau et al., 2018). For example, in smart and Ambient Assisted Living (AAL) environments, it is relatively easy to detect users' current activity but it is difficult to understand or even predict their intention of movement. To deal with this problem, big data fused from an increasing number of sensors and sensing devices are used to understand the full extent of users' personal movement patterns (Suciu, Vulpe, Craciunescu, Butca, & Suciu, 2015). Furthermore, personalization/adaptation should not only consider individuals' preferences, but also other organizational and social factors, such as organizational culture and level of sophistication in the use of technology to collect big data (Vimarlund & Wass, 2014).

2.2.4. Human skills' support

As machines acquire capabilities to learn deeply and actively from data, fundamental changes can occur to what humans are expected to learn in order to live and work meaningfully (Siau, 2018). For instance, under the perspective of symbiotic learning, the human could handle the qualitative subjective judgements and the machine could handle the quantitative elements, an approach that requires tools to support human skill and ingenuity rather than machines which would objectify knowledge (Gill, 2012).

Advanced technologies, including AI, can be used to support human memory, as well as human problem-solving, especially in situations in which a human has to process a huge amount of complex data, or in which a human must make a critical decision quickly or under extreme stress (Hendler & Mulvehill, 2016). Technology to compensate human functional limitations is already in use today in multiple forms, such as personal assistants, reminders, memory and cognition aids, as well as decision support and recommender systems. AI technology is also employed for assisting individuals in managing daily tasks, making purchasing decisions, and managing finances (Hendler & Mulvehill, 2016). In the future, technology can also be used to extend human perception and overcome human senses' limitations, by providing the ability to capture experiences holistically (Schmidt, Langheinrich, & Kersting, 2011). It can also extend human memory capacity and learning ability, by ensuring humans' access to interconnected cognitive intelligent technologies that can assist them in solving typical everyday problems (Wang, 2014). Ultimately, technology could be used to augment human perception and cognition, through the confluence of ICT with the biological brain (Ferscha, 2016). In any case, the view of symbiosis emphasizes that human judgement, tacit knowledge, and intuition, should be united in a symbiotic totality with the potential of machine intelligence, in terms of computability, capacity, and speed (Gill, 2012). Such a development of course currently remains a vision and research objective, but not a tangible reality (Tegmark, 2017). Future endeavors in this area will require further advancements in cognitive sciences, so as to better understand human cognition and the human brain. To that end, cognitive science research can be assisted by recent achievements in ICT, such as big data stemming from human behavior that can provide clues towards understanding basic principles of cognition (Jones, 2016).

2.2.5. Emotion detection and simulation

Humans are emotional and empathetic beings, expressing emotions not only in human-human interactions, but also in interactions with machines. As a result, an important challenge with regard to optimizing human-technology symbiosis refers to how ICT captures and correlates emotional expressions, as well as how technology can express emotions and exhibit empathic behavior (Ferscha, 2016). As technological environments have the potential to affect humans psychologically, it is critical to consider how and when intelligent artifacts may be used for "nudging" individuals for their own or the entire humanity's benefit (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019). For example, "nudging" can be used to help humans manage health conditions, improve lifestyle, or reduce biased judgement (see also the discussion in Section 5.2.1).

Simulated affect poses a moral dilemma, as on the one hand, it promotes human-technology interaction and collaboration, while on the other hand, it may deceive humans who will find it hard to keep in mind that machines do not actually have these affective states and may become emotionally over-attached (Beavers & Slattery, 2017). Besides such inevitable deceptions, there is also the case of deliberate deceptions, when an affective computing system is used in order to persuade people to believe something that is actually false, for example to proceed to a purchase (Cowie, 2015). In this respect, the establishment of a new code of ethics is imperative. The reinforcement of such an ethical code should be safeguarded through a multi-level approach, starting with the education of designers and developers and involving extensive testing and new benchmarking procedures, as it also addressed by the IEEE Global Initiative (2019).

2.2.6. Human safety

In this new context, the targeted autonomous nature of smart environments brings to the surface the paramount importance of human safety, which should be accounted for during design and implementation, but also it should be safeguarded through novel testing procedures. In particular, the development and use of intelligent systems with the potential to self-evolve entails considerable risks, due to technology misuse or poor design (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019). To this end, a recommendation is that advanced intelligent systems should be "safe-by-design," which involves designing architectures using known-safe and more-safe technical paradigms as early in the lifecycle as possible (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019).

At the same time, testing becomes one of the biggest challenges, while existing software testing methodologies cannot cope with the challenges of testing autonomous systems, mainly due to the fact that systems' behavior not only depends on design and implementation, but also on the acquired knowledge of the system (Helle, Schamai, & Strobel, 2016). Furthermore, as AI matures, it will be critical to study its influence on humans and society, on a short-term and long-term basis, which requires engagement with interdisciplinary groups, including computer scientists, social scientists, psychologists, economists, and lawyers, developing assessments and guidance through focused studies, monitoring, and analysis (Horvitz, 2017).

2.2.7. Cultural shift

Beyond technical challenges and shifts, intelligent environments and AI present a cultural shift as well (Crawford & Calo, 2016; Siau & Wang, 2018). As a result, this technological change has to evolve mutually with societal change (Bibri, 2015). In order to achieve a more holistic and integrated understanding of the impacts of smart ecosystems, a social-systems analysis is required, drawing on philosophy, law, sociology, anthropology, science-and-technology studies, as well as on studies of how social, political and cultural values affect – and are affected by – technological change and scientific research (Crawford & Calo, 2016).

Currently, the dominant public narrative about AI is that the increasingly intelligent machines will ultimately surpass human capabilities, will render us useless and steal jobs, and possibly even will escape human control and kill humans (Husain, 2017; Kaplan, 2016). Creating smart ecosystems that will be broadly trusted and utilized requires changing current beliefs and attitudes of the general public, which can be achieved through a careful reassessment of the purpose, goals, and potential of the field (Kaplan, 2016; Siau, 2018). In order to be convincing to the public and to the scientific community, detailed analyses of the challenges regarding ethics and privacy, as well as design approaches with their inherent views about the role of humans are needed when generating claims for future developments (Streitz, Charitos, Kaptein, & Böhlen, 2019).

2.3. Summary of emerging requirements

The issue of symbiosis of humans with smart ecosystems is complex and multi-faceted, extending beyond technical boundaries to a multi-disciplinary approach with the aim to also address ethical, societal, and philosophical compelling issues (Table 2). This symbiosis entails a number of considerations, such as incorporating human values in the design choices and trade-offs such as, for example, between automation and human control, working strategically towards becoming more driven by humanistic concerns than deterministic ones, and taking into account the social dynamics involved (Bibri, 2015). The above factors should be combined with a number of practical concerns, which include, but are not limited to, designing meaningful human control, ensuring systems' transparency and accountability, and accounting for intelligent systems' inherent opacity and unpredictability. A collection of resources compiled by the "People + AI Research" initiative at Google offers guidelines on how to build better AI enabled products, including how to plan for co-learning between users and the AI, how to calibrate user trust given actual AI capabilities, how to explain AI output, and how to support collaborative decision-making between people and AIs (Google, 2019). Ultimately, a key success factor for intelligent systems will be whether they are designed to work truly in concert with users (Holmquist, 2017). To this end, such environments should support and empower humans, by providing personalized, adaptive, responsive, and proactive services; they should support human skills and ingenuity, recognize and respond to human emotions and exhibit empathy without undue manipulation, and above all, they should foster human safety.

3. Human-environment interactions

3.1. Definitions and rationale

Interactions in smart environments and ecosystems are in the process of being radically transformed, shifting from "conventional interaction and user interfaces towards human-centric interaction and naturalistic user interfaces" (Bibri, 2015, *p*. 259). Nowadays, technology is used beyond the organizational context; user interfaces are already far beyond the desktop metaphor, and interactions have advanced from keyboard-and-pointer to touch-and-gesturing.

Streitz (2007) formulated a shift from human-computer interaction (HCI) to human-environment interaction (HEI), because people will increasingly be confronted with collections of devices constituting smart environments. In many cases, computing devices will be embedded in everyday artefacts as "disappearing computers" (Streitz et al., 2007), creating new challenges for providing appropriate interaction affordances. Since then, new technological advancements have already shaped an expanded user interface design space, where the notion and definition of user interfaces acquire new perspectives, and the interactive materials are far more enriched (Janlert & Stolterman, 2015). There is already a rich discussion regarding the implications of increased interactivity (Agger, 2011; David, Roberts, & Christenson, 2018; Elhai, Dvorak, Levine, & Hall, 2017; Janlert & Stolterman, 2017; Sarwar & Soomro, 2013). Taking

Table 2. Summary of main issues and challenges for human-technology symbiosis.

Main Issues	Challenges
Meaningful human control	• Design trade-offs: human control vs. automation • Transparency • Accountability • Understandability: inherent systems' opacity and unpredictability
Humane digital intelligence	• Support for individual and social life • Human rights and privacy • Enabling humans to exploit their potential • Incorporate human values in the design choices • Technology adoption determined by new factors, such as technology alignment with human values
Adaptation and personalization to human needs	• Evolvement of techniques to incorporate AI and big data • Consideration of organizational and social factors besides individual preferences
Human skills' support	• Support of human skills and ingenuity • Enhancement and extension of human memory and human problem solving • Extension of human perception • Advancement of the understanding of human cognition and human brain • Augmentation of human perception and cognition
Emotion detection and simulation	• Capturing and correlation of human emotional expressions • Technology exhibiting emotions and empathic behavior • Addressing inevitable and deliberate deceptions • Development of a new code of ethics for designers and developers
Human safety	• "Safe by design" advanced intelligent systems • New testing methodologies • Multidisciplinary approaches to the influence of AI on humans and society
Cultural shift	• Evolvement of societal change along with technological change • Social-systems analysis • Detailed analysis of the challenges regardingethics and privacy • New design approaches with their inherent views about the role of humans

into consideration that the nature of the new technologically enriched, autonomous, and intelligent environments will bring about novel implications and challenges, the topic of supporting human interactions in these environments becomes a challenge that should not be overlooked in view of the other prominent issues related to user control, transparency, ethics, and privacy (see Section 2 and Section 4).

3.2. Main research issues and state of the art

3.2.1. Interactions in the physical and digital continuum

Interactions in smart environments and ecosystems will become more implicit (Bibri, 2015), often concealed in the continuum between the physical and the digital (Conti et al., 2012). In such 'hybrid worlds', one also has to consider representations of real objects in the virtual domain and vice versa: virtual/digital objects in the physical/architectural domain (Streitz, Geißler, & Holmer, 1998). Of course, there is no one-to-one mapping of all objects between the two domains, because not all objects have counterpart representations in all domains, which has strong implications for interaction design.

A major challenge for designing interaction with smart artifacts, embedded and integrated into the environment, and soon with smart materials, concerns the disappearance of the 'computer' as a 'visible' distinctive device (Norman, 1998). This takes place either physically, through integration in the environment, or mentally from our perception (Streitz, 2001), thus providing the basis for establishing a 'calm technology' as envisioned already by Weiser (1991). In such environments, computers become part of the furniture (*e.g.* as shown in the Roomware® environment with interactive tables, walls, and chairs) (Tandler, Streitz, & Prante, 2002), and decoration (Aylett & Quigley, 2015). The fact that computers "disappear" when embedded in the environment, raises the concern of how humans perceive the interactivity of an object and how they regard it as an interaction partner (Sakamoto & Takeuchi, 2014).

One of the main design challenges in such contexts is that 'users' are in many cases not anymore fully aware of the interaction options that are provided in their current smart environments, because traditional 'affordances' (Norman, 1999) are not available anymore. However, it is reassuring in this respect that users are able to extend existing knowledge and interaction habits from the digital to the physical world, as reported in the study of Interactive Maps, a system featuring touch-based interaction with physical printed maps (Margetis, Ntoa, Antona, & Stephanidis, 2019). Additional challenges for interactions in environments comprising multiple interactive objects and systems include how can users successfully address a specific system, how does the system acquire the appropriate context for a given command, and how can fundamental design principles – such as feedback and recovery from error – be effectively applied (Bellotti et al., 2002).

Moreover, the miniaturization of computers has made it possible to also embed interaction in jewelry and haute couture (Aylett & Quigley, 2015; Seymour & Beloff, 2008; Versteeg, van Den Hoven, & Hummels, 2016). Smart wearable devices, such as glasses, watches, and bracelets, are already commercially available today; however, they have not become mainstream and exhibit a slower diffusion than other portable technologies, such as smartphones (Adapa, Nah, Hall, Siau, & Smith, 2018; Kalantari, 2017). It is noteworthy that the acceptance of wearable devices is influenced by aesthetic factors, such as compelling design and uniqueness (Adapa et al., 2018), even involving cuteness as an emotional appeal (Marcus, Kurosu, Ma, & Hashizume, 2017). Therefore, such artifacts have a twofold essentiality, being perceived by consumers as a combination of 'fashion' and 'technology, namely as "fashnology" artifacts (Rauschnabel et al., 2016). Nevertheless, despite the excitement and promises that are brought by the new potentiality of hiding computers in everyday objects, furniture, and accessories, there is the risk of eventually reaching an ever-increasing society of information overload, information exploitation, and information inequality (Aylett & Quigley, 2015).

3.2.2. Implicit interactions

Interactions are anticipated to be not only conscious and intentional, but also subconscious and even unintentional/incidental, or in the periphery of attention, where they are subconscious yet intentional with direct but imprecise control (Bakker & Niemantsverdriet, 2016; Dix, 2002). Despite the fertility in terms of interaction possibilities, a major point of concern, when designing for such environments, is how to create interaction-intensive but still not-too-invasive experiences.

It is also important to consider how better to support the inevitable shifts of interaction between the center and periphery of attention (Bakker, Hoven, & Eggen, 2015). In any case it must be ensured that the interactive environment does not impose high perceptual and cognitive demands upon users, nor does it create other negative consequences, such as confusion or frustration. Besides design concerns, implicit interactions in intelligent environments raise privacy concerns. From a technical point of view, in order to support such interactions, it is required that the environment records contextual and user data (such as movement or speech), and carries out all the required analysis so as to respond accurately and appropriately (McMillan, 2017). A more detailed discussion of the privacy and ethics concerns, and the challenges entailed is presented in Section 4.

3.2.3. Novel and escalated interactions

At the same time, in the near future, novel forms of interaction can potentially arise, which exploit sensing the environments and simulating human senses. Currently, the senses mostly employed in interaction with technology are vision, hearing, and touch, whereas taste and smell remain largely unexplored (Obrist et al., 2016). Interactions in future environments, however, have the potential to be multisensorial, including digitized chemical senses, such as taste and smell (Spence, Obrist, Velasco, & Ranasinghe, 2017), as well as haptic sensations (Schneider, MacLean, Swindells, & Booth, 2017). Furthermore, other forms of natural interaction are a *sine qua non* for intelligent environments, including facial expressions, eye movements, hand gestures, body postures, and speech, which can be used multi-functionally to acquire context as implicit input, to recognize emotions, to denote explicit inputs, and to detect multimodal communication behavior (Bibri, 2015).

It is therefore evident that interaction will be considerably escalated in terms of available options, potential combinations, and technical requirements. Additionally, design will no longer focus on a single user-artifact interaction. It will have to account for entire environments and ecologies of artifacts, services, and data, as well as for larger user populations, distributed in various different physical locations and contexts of use (Brown, Bødker, & Höök, 2017). This larger context cannot be addressed by simply adding more users, data, or artifacts in the design process; instead, it challenges existing methods to scale up, calling for new design methods (Brown et al., 2017).

Design approaches focusing on the human, such as user-centered design and human-centered design, are highly relevant and extremely important in the context of the forthcoming intelligent environments. This is particularly true since their main objective is how to ensure that technology serves users' needs in the best possible way, a perspective that is claimed to – and apparently should – constitute the ultimate goal of the new technological realm. Still, such design approaches need to evolve, so as to face the emerging challenges, in terms of acquiring and framing the potential contexts of use, eliciting and analyzing user requirements, producing designs, and carrying out evaluations (Marcus, 2015a; Stephanidis, 2012).

3.2.4. Interactions in public spaces

The aforementioned concerns and challenges become even more intricate in the context of public spaces with multiple users. Research in the area is active, exploring various user roles and interaction types, and proposing models and frameworks for the design of interactions in public spaces. In brief, users can be characterized with regard to their interaction with a public system as passers-by, bystanders, audience members, participants, actors, or dropouts (Wouters et al., 2016). A major consideration is how can interactive systems attract the attention of passers-by and motivate them to engage with the system (Müller, Alt, Michelis, & Schmidt, 2010). Factors that have been found to motivate engagement with public systems include challenge, curiosity, choices offered, fantasy, collaboration with other users, one's self-efficacy with technology, as well as the content and appeal of the topic of an interactive artifact (Hornecker & Stifter, 2006; Margetis et al., 2019; Müller et al., 2010).

Another concern for interaction design is the ubiquity of technologies in public settings that "blurs" the boundaries between private and public interaction (Reeves, 2011). For instance, how should a third party experience the interaction of a user with a public interactive system, and how can such a system accommodate transitions between users? In this respect, the design of interactive experiences in public spaces needs to provide clear and timely feedback about who is in control of the interaction, to clarify what each user is in control of (in the case of multi-user systems), and to appropriately support the various user roles in terms of (social) interaction and content (Hespanhol & Dalsgaard, 2015; Hespanhol & Tomitsch, 2015). The "blurred" boundaries between private and public interaction also raise privacy concerns regarding personal information that may be publicly presented, and about how can such "harmless" personal information be defined (Vogel & Balakrishnan, 2004) (see also Section 4).

Furthermore, a characteristic of interactions in public spaces is that they are transient. Cities and airports are good examples of "transient spaces", where multi-user as well as multiple-devices activities take place, and which are increasingly transformed to smart cities and smart airports (Streitz, 2018). The transient nature of interactions in public spaces, as well as the need for catering for a wide variety of potential user characteristics (*e.g.* age, gender, cultural background, technology familiarity) pose additional design requirements

(Hespanhol & Tomitsch, 2015). These include calm aesthetics, support for short-duration fluid interactions, and immediate usability (Vogel & Balakrishnan, 2004). New methods for user participation in the design process are also required (Christodoulou, Papallas, Kostic, & Nacke, 2018). Other challenges stemming from the need to serve different users simultaneously include the balance between the single-user and multi-user contexts, and the facilitation of collaboration among multiple users who may be strangers (Ardito, Buono, Costabile, & Desolda, 2015; Lin, Hu, & Rauterberg, 2015).

3.2.5. Interactions in virtual and augmented reality

Virtual Reality (VR) is one of the "scientific, philosophical, and technological frontiers of our era" (Lanier, 2017, *p.* 1), posing unprecedented challenges, as it provides a realistic representation of imaginary worlds and allows to navigate and interact in an illusionary environment with virtual objects and characters, who may actually represent physical persons located anywhere in the world. Recent technological advancements have made VR available at consumer prices, while most market forecasts suggest that VR will soon have a major impact (Steinicke, 2016).

Key elements to the VR experience are immersion, presence, and interactivity, as well as the virtual world, its creators and participants (Ryan, 2015; Sherman & Craig, 2018). In the recent past, the greatest challenges in the field revolved around developing better hardware systems (Steinicke, 2016). Having already achieved substantial progress in terms of devices, the challenge now lies in creating realistic experiences, exhibiting increased feelings of immersion and presence. This involves advances in sense of embodiment, which includes sense of self-location, sense of agency, and sense of body ownership (Kilteni, Groten, & Slater, 2012). Obstacles in delivering realistic experiences, which need to be overcome, include user cyber-sickness, lack of realistic simulation of locomotion, inadequate self-representation, and lack of realistic visual-haptic interaction (Steinicke, 2016). As Virtual Reality becomes more and more immersive and realistic moving towards real virtuality (Chalmers, Howard, & Moir, 2009), a tangible risk lies in users becoming addicted to virtual worlds and over-attached to virtual agents (see also Section 4.2.4).

Recent trends towards interconnected VR (Bastug, Bennis, Médard, & Debbah, 2017) reveal new possibilities for social experiences in VR and stimulate research to address novel UI and interaction design requirements, evaluation methods, as well as privacy and ethics concerns. At the same time, pertinent design guidelines need to be further elaborated and expanded to also include aspects of social interactions in virtual environments (Sutcliffe et al., 2019). With regard to user experience evaluation, current approaches typically employ subjective user assessment of presence and immersion, whereas future activities should move towards merging such assessments with objective metrics and observations. Advancing research on VR user experience could further produce new guidelines and practices for the design of VR environments.

As technological advances are gained and user acceptance increases, the future also holds promise for Augmented Reality (AR). AR allows the user to interact with a digital layer superimposed on their physical real world. The technology is still in the early stages, but when it reaches its full potential, it is expected to disrupt and transform the way we communicate, work, and interact with our world (Van Krevelen & Poelman, 2010). Some say the combination of voice commands, AI, and AR will make screens obsolete (Scoble & Israel, 2017). The potential for geographic AR experiences, messages (overt or covert), and storytelling is immense (Yilmaz & Goktas, 2017). 'Reality' related technologies that are part of the current and emerging information landscape have the potential to alter the perception of reality, form new digital communities and allegiances, mobilize people, and create reality dissonance. These realities also contribute to the evolving ways that information is consumed, managed, and distributed. A major challenge in this respect is how AR as a new medium will combine the real and virtual in such a unique way that the provided experience cannot be derived exclusively either from the real or from the virtual content (Azuma, 2016).

3.2.6. Evaluation

Evaluation in intelligent environments should go beyond performance-based approaches to the evaluation of the overall user experience, while it should take place in real-world contexts (Gaggioli, 2005). Traditional evaluation practice has been pointed out as insufficient for new interactive systems that feature new sensing possibilities, shifts in initiative, diversifications of physical interfaces, and shifts in application purpose (Poppe, Rienks, & van Dijk, 2007). Challenges include the interpretation of signals from multiple communication channels in the natural interaction context, context awareness, the unsuitability of task-specific measures in systems which are often taskless, as well as the need for longitudinal studies to assess the learning process of users (Poppe et al., 2007).

Taking into account the immense number of quality characteristics that should be evaluated in such environments (Carvalho, de Castro Andrade, de Oliveira, de Sousa Santos, & Bezerra, 2017), it is evident that new assessment methods and tools are required, complementing self-reported or observed metrics with automatically acquired user experience indications (Ntoa, Margetis, Antona, & Stephanidis, 2019). Finally, new frameworks and models are needed in order to provide holistic and systematic approaches for the evaluation of UX in intelligent environments, taking into account a wide range of characteristics and qualities of such environments (Ntoa, Antona, & Stephanidis, 2017; Scholtz & Consolvo, 2004).

In the future, intelligence can transform into a service and become a new design material (Holmquist, 2017). In fact, Artificial Intelligence as a Service (AIaaS) is already available today, with the aim to assist data scientists and developers in delivering applications employing AI without having technical know-how (Janakiram, 2018; Sharma, 2018). Similarly, AI as a design material could be plugged into applications or artifacts, facilitating designers throughout iterative design and evaluation. Such a perspective points to a direction in which intelligence is used as a tool to truly empower experts and technology becomes an even more valuable tool (Klein, Shneiderman, Hoffman, & Ford, 2017). At the same time, it brings to the foreground the need for establishing concrete guidelines and a code of ethics for the design and development of AI applications, services, and artifacts; it also highlights the requirement for evolving the existing design, evaluation, and testing procedures.

3.3. Summary of emerging requirements

In summary, interaction in forthcoming technological environments will radically shift and will be considerably escalated as users' location, posture, emotions, habits, and intentions will constitute candidate input data to a variety of visible and invisible technological artifacts embedded in the environment. Robotics and autonomous agents will be typically included in such technologically enriched environments. Information will be communicated from the one interaction counterpart to the other naturally, while the digital will coexist with and augment the physical. These new challenges pave the way towards evolving the existing design and evaluation methodologies and techniques to encounter, embrace, and eventually employ future technologies to their benefit. Table 3 summarizes the aforementioned concerns and challenges, as they stem from interaction-related issues. The important role of Human-Environment Interaction will increasingly show in the context of designing interaction in smart cities.

Last, but definitely not least, it is crucial to comprehend how the new interaction possibilities in technologically enriched environments affect the human. As Norman (2014) put it: "Technology is not neutral; it dominates", as it poses a way of thinking about it to those who are directly or indirectly influenced by it; the more successful and widespread a technology is, the greater its impact is upon the entire society. As technologies become smarter, pervasive, yet invisible, and able to recognize, respond to, and even anticipate human needs and wishes, users tend to attribute personality, agency, and intentionality to them (Marenko & Van Allen, 2016). The design of interactions therefore can be seen as "designing relations between humans and the world, and, ultimately designing the character of the way in which we live our lives" (Verbeek, 2015, *p*. 31).

4. Ethics, privacy and security

4.1. Definitions and rationale

Aristotle wrote in his *Rhetoric* that the triplex *ethos-pathos-logos* are the three main attributes that affect the ability of orators to convince their audiences. *Ethos* is the characteristic of speakers that can make them trustworthy, because we tend to give our trust to honorable persons. *Pathos* is related to putting the audience into a certain frame of mind, as persuasion may occur when the speech evokes specific emotions. *Logos* refers to the proof provided by the words of the speech itself, meaning that persuasion may be achieved when the truth is proven through appropriate argumentation. Humans' relation with technology-augmented environments resembles more a dialogue than a rhetoric, still it is a fact that people will be persuaded by these environments (and will eventually accept and adopt them) if they are ethical, if they raise positive emotions to their users and if they actually prove to be worthy to trust.

Ethics, privacy, trust and security have always been important concerns in relation to technology, acquiring yet new dimensions in the context of technologically augmented and intelligent environments. It is indicative of the importance and timeliness of ethics that there is a plethora of relevant articles in the literature for every newfangled technological domain, such as AI, AmI, big data, Internet of Things (IoT), autonomous agents and robotics, as well as mobility services, *e.g.* automated driving (Biondi, Alvarez, & Jeong, 2019; Dignum, 2018; Tene & Polonetsky, 2013; Ziegeldorf, Morchon, & Wehrle, 2014). It is also noteworthy that there are specialized communities and organizations[1] dedicated to exploring and developing the topic of ethics and ethical intelligence (Becker, 2008; Marcus, 2015b). Aligned with these concerns, and motivated by the importance of ethics for human-technology symbiosis in technology-augmented and intelligent environments, this chapter explores critical issues related to ethics, privacy, and security as they emerge in such contexts.

4.2. Main research issues and state of the art

4.2.1. HCI research

As interactive technologies pervade every life domain, HCI research is challenged to move beyond lab studies and expand to new fields and contexts, carrying out research "in the wild" (Crabtree et al., 2013). Research in public spaces, in particular, faces the dilemma of following typical procedures to inform participants and acquire their consent *vs*. studying the actual user experience and behavior, which can be influenced if participants are aware that they are being observed (Williamson & Sundén, 2016). Similar ethical concerns about engaging participants in studies revolve around museums or research at the intersection of art and technology, where the distinction between research participants and event audience is not clear (Fiesler et al., 2018).

Another point of caution for HCI research refers to involving vulnerable user populations, such as older adults, people with disabilities, immigrants, socially isolated individuals, patients, children, *etc*. Besides issues regarding participants' understanding of the study and giving their consent, there are also concerns related to managing participants' misunderstandings, handling potentially erroneous and optimistic expectations about technology, and attending to problems that may occur when the technology does not perform as expected (Waycott et al., 2016).

The recent technological evolution has raised new issues related to the usage of online data in HCI research, such as the usage of data without subjects' consent. In this case, a fundamental question is if researchers are entitled to using data without consent, especially in cases that data are publicly available (Frauenberger, Bruckman, Munteanu, Densmore, & Waycott, 2017; Vitak, Shilton, & Ashktorab, 2016). Other open questions refer to what constitutes public data and what are the best practices for acquiring informed consent (Frauenberger et al., 2017). Participant anonymity is also a challenging undertaking, as studies have identified that it is possible to de-anonymize data when paired with other datasets (Vitak et al., 2016).

4.2.2. Online Social Networks (OSNs)

Privacy in OSNs is a major point of concern, and indicative of the discussion on privacy in all technological domains. Privacy can be defined as "a human value consisting of a set of rights including solitude, the right to be alone without disturbances; anonymity, the right to have no public personal identity; intimacy, the right not to be monitored; and reserve, the right to

Table 3. Challenges stemming from interaction-related issues in intelligent environments.

Main Issues	Challenges
Interactions in the physical and digital continuum	● The computer “disappears” as a “visible” distinctive device ● New types of affordances for disappearing computers/devices ● Successful direction of user commands to the appropriate interactive artifact ● Appropriate user command interpretation according to the current context ● Effective application of established design principles (*e.g*. feedback and recovery from error) ● Perceivable interactivity of everyday objects ● “Fashnology” artifacts perceived as a combination of fashion and technology ● Risk of information overload, information exploitation, and information inequality
Implicit interactions	● Appropriate support for shifts of interaction between the center and periphery of attention ● Design for interaction-intensive experiences that are not invasive ● Risk of high perceptual and cognitive demands, confusion, or frustration ● Ethics and privacy issues
Novel and escalated interactions	● Natural interaction and novel forms of interaction ● Multisensorial interactions ● Escalated interaction, involving ecologies of artifacts, services and data, and addressing larger user populations ● New/updated methods for acquiring and framing contexts of use, eliciting and analyzing user requirements, as well as producing designs
Interactions in public spaces	● Attracting the attention of passers-by and motivating them to engage with the system ● Ubiquity of technologies ● Transient spaces in smart cities and smart airports ● Support for various user roles and styles of engagement with the system in terms of (social) interaction and content ● Privacy of personal information ● Transient use ● Wide variety or potential user characteristics ● Accommodation of user transitions and balance between single-user and multi-user contexts ● Facilitation of user collaboration even among strangers
Interactions in virtual and augmented reality	● Realistic VR experiences ● Advanced sense of embodiment, realistic simulation of locomotion and adequate self-representation in VR environments ● Overcoming limitations of cyber-sickness in VR environments ● Achieving realistic visual-haptic interaction in VR environments ● Pursuit of social VR User Experience ● User experience evaluation in VR, combining subjective assessments with objective measurements ● Successfully blending the real and virtual worlds to provide a unique seamless experience in AR
Evaluation	● Interpretation of signals from multiple communication channels, context awareness, unsuitability of task-specific measures in systems which are often task-less ● Evaluation of the overall UX beyond performance-based approaches ● New methods and tools, taking advantage of the intelligent infrastructure towards automatically calculating UX metrics, besides self-reported or observed metrics ● Intelligence offered as a service and as a design material ● Comprehension of the impact of the new interaction possibilities in intelligent environments on the human ● Development of a code of ethics for the design and development of intelligent applications, services, and artifacts

control one's personal information, including the dissemination methods of that information" (Kizza, 2017, *p.* 303).

Privacy concerns in OSNs include who can view one's private information, the ability to hide information from a specific individual or group, the degree to which other users can post and share information about an individual, data retention issues, the ability of the employees of the OSN to browse private information, selling of data, and targeted marketing (Beye et al., 2012). Interestingly though, despite their privacy concerns, individuals reveal personal information for relatively small rewards, a phenomenon which is referred as the "privacy paradox". Kokolakis (2017) identifies a number of potential factors for this paradox, including that the use of OSNs has become a habit and is integrated into daily life, that the perceived benefits of participation outweigh observed risks, that individuals do not make information-sharing decisions as entirely free agents, and that privacy decisions are affected by cognitive biases and heuristics, as well as by bounded rationality and incomplete information. Privacy in OSNs becomes even more crucial when these are used by sensitive user groups for specialized purposes (*e.g.* school communities and learning OSNs used by students) (Parmaxi, Papadamou, Sirivianos, & Stamatelatos, 2017). Privacy and content sharing (and therefore sociability) constitute two conflicting fundamental features of OSNs, which however need to be perfectly joined, a challenge that designers of OSNs have to master (Brandtzæg, Lüders, & Skjetne, 2010).

Towards raising awareness and protecting user rights, the European Parliament and Council of the European Union issued the regulation 2016/679 of the General Data Protection Regulation (GDPR) on the protection of natural persons with regard to the processing of personal data and on the free movement of such data. Being legally in effect since May 25, 2018, GDPR regulates processing of the data, and the rights of the data subject, including transparent information and communication for the exercise of rights, the right of access, as well as the right to rectification, erasure, restriction to processing, and data portability (European Commission, 2016).

4.2.3. Healthcare technologies

Social media are often used in the context of healthcare ICT to facilitate information exchange, and to create media content individually or shared with specific groups (Denecke et al., 2015). In this context, ethical issues include the use of social media for underage or older persons, as well as using social media for research purposes, such as to harness patient-reported data, to conduct online surveys, and to recruit participants (Denecke et al., 2015).

Data privacy, accuracy, integrity and confidentiality become an even greater concern in the context of healthcare, whether it pertains to social media, telehealth, electronic health records, wearable health sensors, or any other eHealth domain (George, Whitehouse, & Duquenoy, 2013). Additional ethical principles that should be addressed in the eHealth context include access for all to eHealth (see also Section 5.2.5), anonymity, autonomy, beneficence and non-maleficence, dignity, no discrimination, free and fully informed consent, justice, safety, and value-sensitive design (Wadhwa & Wright, 2013). Telehealth ethical concerns also extend to the impact that distant care may have on the healing relationship that is typically developed between patients and health providers, the loss of touch, and the danger that virtual visits may replace actual doctor visits in the name of cost/time effectiveness (Fleming, Edison, & Pak, 2009). With regard to patients' data, concerns pertain to the question of legitimacy of purpose, and the potential for data exploitation (Fleming et al., 2009). Furthermore, an often neglected yet critical issue is that of liability, as patients become active participants in the delivery of healthcare, raising the issues of potential mistakes, misreports, or misinterpretations (Kluge, 2011).

Another aspect contained in all of the above technologies is the prevalence of persuasion techniques to change people's behavior. While some objectives for the purposes of health (quitting smoking, weight maintenance, nutrition habits, exercise routines, *etc.*) are usually valuable and desirable, persuasive technologies could, in the wrong circumstances, be used to delude people or to persuade them to engage in undesirable behavior. Mobile products (Marcus, 2015b) and social media are especially vulnerable to these distortions and need to be assessed as technologies develop and mature. An extended discussion, including ethical concerns, on technology that fosters well-being health and human eudaimonia is presented in Section 4.3.

4.2.4. Virtual reality

VR is a technological domain, in which – due to the illusion it creates – two major social and ethical themes are raised: (i) reactions and feelings of the user, such as over-attachment to virtual agents, or feeling out of control and behaving with hostility in the virtual environment and outside in the physical world, as well as (ii) the intentions of the VR environment creator, which may be obscure and dangerous for the user, *e.g.* by collecting information or inducing mental/psychological transformations without the user's knowledge (Kizza, 2017). VR allows the user to step in a "reality", which can be entirely synthetic and a created digital environment, or it could be a suspended moment of an actual real-world environment. The synthetic environment could be modeled after the real world, a fantasy, or both. Most virtual realities do not fully cross over the uncanny valley (Mori, MacDorman, & Kageki, 2012), but this is an issue that is expected to improve in the future.

A recent tangible example of attachment to virtual characters is the marriage of a man with a virtual character, which was asserted by the company producing the holograms with a marriage certificate,[2] opening a wide discussion regarding the indisputable freedom of the individual, the role of technology in affecting free will, and the ethical dilemmas/responsibilities of technology creators and designers. Even more crucial than over-attachment to virtual agents is the concern of how social interactions may be reshaped in a VR context, leading for example individuals to opt out of societal engagements (which can have far-reaching implications on fertility rates, the economy, and existing social fabrics), or providing the option to virtually extend one's life beyond physical death (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019).

4.2.5. IoT and big data

The IoT paradigm is characterized by heterogeneous technologies, including smart objects that are interconnected and cooperate over the Internet infrastructure, enabling many new services and making buildings, cities, and transport smarter (Ziegeldorf et al., 2014). In this highly interconnected and heterogeneous environment, where any interactions may occur between humans, devices, and autonomous agents, new privacy and security threats are manifested.

In particular, privacy will become even more important in the smart hybrid cities to come (Streitz, 2018). In the virtual world, people can use fake identities and anonymization services. This will be difficult or even impossible in the real world. Data existing about people in the virtual world are now complemented by and combined with real world data and vice versa. Public and private Closed Circuit Television (CCTV) cameras are taking pictures of people entering a shop or a restaurant with known locations, while face recognition identifies personal identities. Real objects that people are wearing, carrying, using, buying will be recognized by sensors in the environment because these objects are tagged. Increased instrumentation of vehicles in the context of autonomous driving affects privacy. Personal walking behavior is transparent when carrying a smartphone. Thus, it will become more and more difficult to avoid object and person tracking, and, the challenge of preserving privacy in the real/hybrid world will be immense in IoT enabled environments.

Big data goes hand in hand with IoT, both being recent technological evolutions that will definitely constitute core components of future technologically augmented environments. Big data, due to the harvesting of large sets of personal data coupled with the use of state of the art analytics, outlines additional threats to privacy, such as automated decision making (when decisions about an individual's life are handed to automated processes), which raises concerns regarding discrimination, self-determination, and the narrowing of choices (Tene & Polonetsky, 2013). For example, predictive analytics may hinder implications for individuals prone to illness, crime, or other socially unacceptable characteristics or behaviors (Tene & Polonetsky, 2013). Other obscure possibilities are individuals (mistakenly) being denied opportunities based on the actions of others, the reinforcement of existing inequalities for vulnerable user groups (*e.g.* low-income consumers), as well as malevolent attempts and misleading offers to vulnerable individuals, such as seniors with Alzheimer or individuals with addictions (Federal Trade Commission, 2016). Responsible and fair data management and analysis is required from researchers to avoid inducing bias and discrimination (Stoyanovich, Abiteboul, & Miklau, 2016).

4.2.6. Intelligent environments

It is evident that ethics, privacy, and trust are topics that span all technological domains, with their main questions being common. Nevertheless, the different domains pose supplementary concerns. For instance, biometrics in general pose the same threats to data privacy as any other user data (*e.g.* unwarranted identification and threats to the individual, undesired collection of personal data, and unauthorized access to personal information), however they also impose an additional moral dilemma because biocentric data has an impact on one's right to control the use and disposition of one's body (Alterman, 2003).

Likewise, intelligent environments invoke the same ethical concerns with other developing technologies, especially with those technologies that raise questions about how humans understand ourselves and our place in the world (Boddington, 2017). In general, intelligent systems entail a number of risks, including users' identification based on collected data, permanence of personal/sensitive data, profiling and implicit deduction and attribution of new properties to individuals, use of data for monitoring, misinterpretation of data, public disclosure of confidential information, as well as collection of data and applying persuasion techniques without the user's awareness (Jacucci, Spagnolli, Freeman, & Gamberini, 2014). Despite the potential of the system to acquire and retain large amounts of (personal) data, this collection should be limited (Könings, Wiedersheim, & Weber, 2011). In fact, there is a tricky trade-off between creating smartness and providing or maintaining privacy. Obviously, a smart system can usually be 'smarter' with respect to a service offered, if it has more knowledge about the person compared to a system with no or insufficient data. The challenge is now to find the right balance. Determining the balance should be under the control of the involved person and would also imply that people are willing to pay for a service – not with their data but with money. This requires transparency about the options and real differentiated choices. Extending the rules and concepts laid out in the GDPR (European Commission, 2016) would be one direction to further develop these ideas. Privacy should be also examined from the perspective of rules that govern information flows according to our values and norms, so that an ethical system of privacy rules develops for the benefit of humans in intelligent environments, embedded as an essential component of these future environments (Richards & King, 2016).

When it comes to AI and autonomous agents, a fundamental ethical concern is that of responsibility: where does responsibility lie, what are the moral, societal and legal consequences of actions and decisions made by an AI system, and can an AI system be held accountable for its actions (Dignum, 2018)? Ethical decision making in AI is a multi-disciplinary field of research that is called to provide answers to such dilemmas and safeguard our future. Moral decision-making by humans involves utilitarian considerations and moral rules, which often involve sacred values that may be acquired from past example cases and may also be culturally sensitive (Yu et al., 2018). As AI systems are constructed by humans, an approach is to integrate societal, legal and moral values into all the development stages of AI systems, so that AI reasoning takes into account these values, weighs their priorities when it comes to different stakeholders in various multicultural contexts, explains its reasoning and guarantees transparency (Dignum, 2018). Asimov's three laws of robotics (Asimov, 1950) are often considered an ideal set of rules for machine ethics, however, there are arguments that show these laws may not be adequate (Anderson, 2008). An alternative approach advocates for shifting the burden of moral reasoning to autonomous agents, and enabling agents to behave ethically and to judge the ethics of other agents. This can be achieved by developing primary rules that will allow the creation of secondary rules, as well as the modification and substitution of rules as situations evolve (Yu et al., 2018). Man-Machine Rules can help organize dialog around questions, such as: how to secure personal data, how ethical are chips embedded in people and in their belongings, what degrees and controls need to be taken into account for personal freedoms and risks, and whether consumer rights and government organizations will audit algorithms (Dellot, 2017). Challenges involved in embedding values and norms in autonomous intelligent systems include the need for norm updating similar to how humans update their norms and learn new ones, the conflicting norms that AIs will face and how to resolve those conflicts, that not all norms of a target community apply equally to human and artificial agents, and that biases may be introduced that will disadvantage specific groups (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019).

As autonomous intelligent agents will make increasingly complex and important ethical decisions, humans will need to know that their decisions are trustworthy and ethically justified (Alaieri & Vellino, 2016). Therefore, transparency is a requirement (see also Section 2.2.1), so that humans can understand, predict, and appropriately trust AI, whether it is manifested as traceability, verifiability, non-deception, or intelligibility (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019). Intelligible AI, in particular, will further help humans identify AI mistakes and will also facilitate meaningful human control (Weld & Bansal,, 2019). Nevertheless, depending on how the explanations are used, a balance needs to be achieved in the level of details, because full transparency may be too overwhelming in certain cases, while not enough transparency may jeopardize human trust in AI (Chen et al., 2018; Yu et al., 2018). At the same time, system transparency and knowing that AI decisions follow ethics will influence human-AI interaction dynamics, giving the opportunity to some people to adapt their behaviors in order to render AI systems unable to achieve their design objectives (Yu et al., 2018).

4.2.7. Cybersecurity

The issues discussed above mainly revolve around ethics and privacy, highlighting challenges and potential threats. Privacy, however, is coupled with cybersecurity (*aka* IT security), an issue that has become prominent for two main reasons. First, the transformation of our societies, through the expansion of digital technologies, offers more opportunities for cyber-criminal activity (Moallem, 2018). It is not only public organizations and institutions, but also residential units that are now highly digitized (*e.g.* including surveillance cameras, IoT-connected home appliances and medical devices, home control and automation systems, *etc.*). It can be said that every aspect of human activity is managed, recorded, and tracked in the digital realm, even "in person" meetings (Moallem, 2018). Second, cyber-attacks require few expenses, they are geographically unconstrained and involve less risk to the perpetrator than physical attacks (Jang-Jaccard & Nepal, 2014).

Security is a challenging task, especially since the high number of interconnected devices raises scalability issues, making traditional security countermeasures inapplicable (Sicari, Rizzardi, Grieco, & Coen-Porisini, 2015). In addition, as most of the current commercial IoT devices have limited on-board security features, they can constitute an easy target for hacking, blocking, altering their communication, changing their configuration, or sending them false commands (Tragos, Fragkiadakis, Kazmi, & Serrano, 2018). Overall, the main security threats involve data breach and privacy, as well as attacks against the devices or the software of both devices and servers.

Data anonymity and confidentiality are threatened by the connectedness of everyday things, which opens up possibilities for identification of devices through fingerprinting and the possibility to create huge databases with identification data (*e.g.* speech) (Ziegeldorf et al., 2014). At the same time, devices may manage sensitive information (*e.g.* user habits or health data), which entails privacy threats in the case of inventory attacks (by non-legitimate parties), as well as in lifecycle transitions of the devices (Sicari et al., 2015; Ziegeldorf et al., 2014). Additional privacy threats in the IoT context include: the possibility for advanced profiling through inferences by correlations with other profiles and data, exposure of private information through a public medium, as well as linking different systems such that the combination of data sources reveals (truthful or not) information that the individual had not provided and may not wish to reveal (Ziegeldorf et al., 2014). Threats may also occur by malicious attacks against the sensors and activators of intelligent environments. For instance, attackers may steal information regarding the health status of a user who is being monitored and eventually identify when the user is at home or absent (Tragos et al., 2018). By attacking actuators, it may also be possible to control or tamper with house elements (*e.g.* doors and windows, air-conditioning, alarms, *etc.*), which not only causes physical security threats, but also decreases the reliability of the system and therefore the trust that users put in it.

The discussion on cybersecurity in the context of IoT and smart cities is rich from a technical point of view, identifying challenges, proposing architectures, and suggesting future research endeavors. However, despite technical advancements that should be pursued, it has been recognized that the main weak point in breached security is the human agent, be it through error or ignorance (Moallem, 2018; Still, 2016). Therefore, the role of HCI becomes crucial in pursuing usable cybersecurity, in educating individuals so as to raise their awareness and appropriately shape their behavior, as well as in training organizations and institutions on the human side of cybersecurity.

4.3. Summary of emerging requirements

In summary, trust is hard to come by, and requires initial trust formation and continuous trust development, not only through transparency, but also through usability, collaboration and communication, data security and privacy, as well as goal congruence (Siau & Wang, 2018). To this end, technological systems need to behave so that they are beneficial to people beyond simply reaching functional goals or addressing technical problems, by serving human rights and the values of their users, "whether our ethical practices are Western (*e.g.* Aristotelian, Kantian), Eastern (*e.g.* Shinto, Confucian), African (*e.g.* Ubuntu), or from a different tradition" (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019, *p.* 2). The main concerns in this respect refer to privacy and the challenges it raises in the context of the new digital realm, to ethical issues as they appear in the various domains, and to cybersecurity. Table 4 presents a summary of these concerns, as they have been discussed in this section. Additional ethical concerns, pertaining to specific contexts (*e.g.* symbiosis, health, learning), are discussed in the various corresponding sections of this paper.

In conclusion, a new code of ethics needs to be established, pursued in three directions: ethics by design, in design, and for design (Dignum, 2018). In this new code, user privacy should be further shielded, especially since the intelligent technological environments feature such an abundance of information and knowledge about the user, as well as automated information analysis and the potential for opinion forming. In any case, the idea that people can fix the tech world through a voluntary ethical code emergent from itself, paradoxically implies that the people who created the problems will fix them (Simonite, 2018). HCI research should also support regulation activities about privacy, safety, and security in the new intelligence era.

5. Well-being, health and eudaimonia

5.1. Definitions and rationale

Technological advances, coupled with advances in medicine, offer the opportunity to provide more effective and less expensive ways of fostering a healthy life, by promoting and supporting healthy behaviors, encouraging disease prevention, offering new forms of therapy, and managing chronic illness. Improvements in image analytics, computing, large-scale databases, and cloud capabilities in combination with precision medicine, next-generation sequencing and molecular diagnostics that deepen understanding of one's unique biology, have contributed to the development of precision health. Precision health aims to make health care more tailored to each person based on their individual differences and can eventually lead to precision aging, allowing individuals to individualize and optimize care over their lifespan (Dishman, 2019).

Moreover, in a world where technology is omnipresent, the question arises of how its role towards enhancing well-being and human eudaimonia can be optimized. Eudaimonia[3] is a concept that can be traced to classic Hellenic philosophy, and also constitutes a topic of contemporary philosophy. It stands for realizing one's potential, and is associated with several variables including self-determination, a balance of challenges and skills, and the investment of considerable effort (Marcus, 2015d; Waterman et al., 2010). Eudemonic experiences are related to need fulfillment, long-term importance, positive affect, and feelings of meaningfulness, in contrast to happiness that is considered as hedonia or momentary pleasure, such as unwinding and relaxing (Mekler & Hornbæk, 2016). The distinction between eudaimonia and happiness can be useful in our understanding of how technology use may contribute to eudaimonia and people's well-being, and could also inspire new technology designs pursuing meaningful experiences with interactive technology (Mekler & Hornbæk, 2016).

This section discusses the topic of fostering health, well-being, and human eudaimonia through technology and highlights points of concern and challenges as they arise in this context.

5.2. Main research issues and state of the art

5.2.1. Personal Medical Devices (PMDs) and self-tracking

Medical technologies tailored to individuals have proliferated in recent years through PMDs, "devices that are attached to, worn by, interacted with, or carried by individuals for the purposes of generating biomedical data and/or carrying out medical interventions on the person concerned" (Lynch & Farrington, 2017, *p*. 3). Whether or not consumer wearable technology will be adopted and accepted by the medical community, and how this technology can best serve medicine remain unclear and will be determined by two major concerns: (i) how health practitioners will be prepared to accommodate the increasing number of patients who will bring wearable data to their medical consultation appointments, and (ii) the high potential for errors, when patients without medical training attempt to interpret symptoms based on data stemming from devices that may be unreliable (Piwek, Ellis, Andrews, & Joinson, 2016). A point of concern that needs to be addressed for improving the medical trustworthiness of such devices is the trade-off between users' comfort, sensor unobtrusiveness, and signal quality (Arnrich, Mayora, Bardram, & Tröster, 2010).

PMDs do not refer only to dedicated wearable devices (*e.g.* smartwatches), but also to activity monitoring and health promotion applications deployed in smartphones (Lynch & Farrington, 2017). Such applications have the benefit of offering a self-management intervention that is adaptable, low cost, and easily accessible, while research has suggested that the use of such apps has the potential to improve health outcomes for patients with chronic diseases (Sun, Rau, Li, Owen, & Thimbleby, 2016; Whitehead & Seaton, 2016), as well as the potential to promote a healthy lifestyle and physical activity (Dallinga, Mennes, Alpay, Bijwaard, & de la Faille-Deutekom, 2015).

In such cases, persuasive technologies are often employed to aid and motivate people to adopt positive behaviors and avoid harmful ones (see Marcus, 2015c for an example of how persuasion design was employed in a mobile phone application to reduce food consumption and increase exercise). In brief, the persuasive strategies – besides tracking and monitoring – that are typically employed are social support, sharing and comparison, reward points and credits, praise, persuasive images and messages, suggestion and advice, reminders and alerts, as well as collaboration and cooperation with peers (Orji & Moffatt, 2018). Overall, persuasive technology has proved to be effective (Orji & Moffatt, 2018), however, it raises ethical concerns (see also Section 4.2.3). For instance, the widespread manipulation of humans by autonomous intelligent agents could result in loss of human free agency and autonomy and even to deceptions of humans (*e.g.* agents pretending to be another human being) (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019).

The possibility for self-tracking – that is, of "monitoring and recording and often measuring elements of an individual's behaviors or bodily functions" (Lupton, 2016, *p*. 2) – as it is offered by contemporary devices (including PMDs) has recently constituted a popular topic for discussion and debate. The attributes tracked

Table 4. Privacy, ethics and security concerns as they appear in different technological domains.

Main Issues	Privacy and ethics concerns
Fundamental privacy concerns	• Solitude: the right to be alone without disturbances • Anonymity: the right to have no public personal identity • Intimacy: the right not to be monitored • Reserve: the right to control one's personal information, including its dissemination
HCI research	• Research in public spaces with the contradicting requirements of informed consent and observing original (uninfluenced) user behavior • Involvement of vulnerable user populations • Research using online data
Online Social Networks	• Selling of data • Targeted marketing • Reduced user caution regarding privacy, due to habituation of OSNs, incomplete information, and cognitive bias • Persuasive technology used for questionable objectives
Healthcare technologies	• Technology recipients include vulnerable user groups (*e.g.* older persons, children, patients) • Use of social media to harness patient-reported data • Data accuracy and integrity • Accessibility and access for all • Autonomy • Beneficence and non-maleficence • Dignity • No discrimination • Free and fully informed consent • Justice • Safety • Loss of human contact • Legitimacy of purpose • Liability, as users become active participants in the delivery of healthcare
Biometrics	• Violation of one's right to control the use and disposition of one's body
Virtual Reality	• Over attachment to virtual agents • Hostile behavior in the virtual environment • Potentially obscure and dangerous intentions of the VR environment creator • Freedom of the individual *vs.* impact of technology on one's free will • Reshaping of social interactions • Altered perception of reality and reality dissonance
IoT and Big Data	• Data about people in the virtual world are complemented by and combined with real world data • Data anonymity is further threatened by the connectedness of everyday things (e.*g.* identification of personal devices, huge databases with identification data) • Privacy threats in the case of inventory attacks or in lifecycle transitions of devices that carry personal information • Possibility of advanced profiling through correlations with other profiles and data • Privacy and identification threats realized by linking different systems and combining data • Automated decision making may lead to discrimination and narrowing of choices • Potential for reinforcement of existing inequalities for vulnerable user groups • Malevolent attempts and misleading offers towards vulnerable individuals
Intelligent environments	• Attribution of new implicitly derived properties to the individual • Use of data for monitoring • Misinterpretation of data • Applying persuasion techniques without the user's awareness • Design trade-off: smartness vs. privacy • Development of an ethical system of privacy rules • Responsibility • Ethical decision making • Transparency, featuring a balance in the level of details
Cybersecurity	• The high number of interconnected devices raises scalability issues making traditional security countermeasures inapplicable • Most commercial devices feature limited on-board security settings • Malicious attacks against sensors and actuators can threaten physical security and jeopardize trust • The human agent is the main weak point in cybersecurity

may include body state (*e.g.* physical and physiological), psychological state, activities (*e.g.* exercise, diet, and sleep), social interactions, and environmental and property states (Oh & Lee, 2015). Self-trackers vary in their approaches, as some of them may collect data on some dimensions of their lives and only for a short time, while others may do so for a multitude of phenomena and for long time periods (Lupton, 2016). Key UX issues for the adoption of self-tracking have been found to be data controllability, data integration and accuracy, data visualization, input complexity, privacy, aesthetics, and engagement (Oh & Lee, 2015).

Self-tracking provides the potential to actively involve individuals in the management of their health and to generate data that can benefit clinical decision making and research, resulting in improved overall health and greater self-knowledge (Sharon, 2017). PMDs and self-tracking constitute two main sources of small data (rich temporal data from a single person), which have the potential to become more effective when combined and thus lead to more accurate predictions (Dodge & Estrin, 2019). However, integrated analysis and tools to achieve it are still in early stages and constitute a near future goal to achieve, overcoming the current isolation of data analytics that are based on a single data source.

On the other hand, the digitization and automation of self-tracking entails privacy threats and ethical concerns regarding the usage of the data generated (Lupton, 2017; Lynch & Farrington, 2017). In addition, from a sociological perspective, a number of questions arise, including how the concepts of the body, self, social relationships, and behaviors are reconfigured, and what are the implications for data politics, data practices and the digital data economy, as well as what are the power inequalities inherent in self-tracking cultures (Lupton, 2017).

Self-tracking is strongly linked with the concept of quantified bodies, constructing dynamic bodies that produce data and are knowable through specific forms of data, constituting sites of possible intervention, and introducing new risks (Lynch & Farrington, 2017). Critiques to the self-tracking movement include that it opens the path for disengagement of the state from its responsibility for citizens' health, that humans are under surveillance and discipline, that the scientific accuracy and objectivity of self-tracking activities is questionable, and that the acquired metrics are simple numbers that cannot represent the richness and complexity of human nature (Sharon, 2017). All things considered, it is evident that developing self-tracking technologies is much more than a technical task, and hence, a multi-disciplinary approach should be followed that involves software developers, interface designers, clinicians, and behavioral scientists (Piwek et al., 2016).

5.2.2. Serious games for health

A technological intervention that has been used in the context of health is serious games, that is, games used to drive health-related outcomes (Johnson et al., 2016). There are various types of serious games for health, including games for physical fitness (exergaming), education in self-healthcare, distraction therapy (*e.g.* to help individuals with chronic illness to deal with pain), recovery and rehabilitation, training and simulation, and cognitive functioning support (Susi, Johannesson, & Backlund, 2007). An important advantage of using serious games for health purposes is the ability of games to motivate, and as a result they constitute a good way to influence users and keep them engaged in health behavior change (Johnson et al., 2016).

Despite their potential, it has been observed that the broad adoption of health games is difficult to achieve. A considerable challenge faced is that their development involves high design complexity and multi-disciplinary teams, ideally including users in the process, which all result in slower speed of implementation (Fleming et al., 2017). At the same time, user expectations regarding gaming evolve rapidly (Fleming et al., 2017). Therefore, a challenge for serious games approaches is to keep up with user expectations, which are formed through users' experience with the entertainment industry. Nevertheless, trying to "compete" with professional, big studio entertainment games induces additional costs that cannot be practically compensated, as there is no developed market in the field (Johnson et al., 2016).

An additional concern refers to the evaluation of serious games with target users. In particular, the majority of evaluation efforts mainly focus on the usability of the designed games and not on the actual long-term impact of a game on the individual (Kostkova, 2015). Although such long-term evaluation efforts are costlier and demanding, they are crucial for the evolution and user acceptance of health games. IoT and big data are technological advancements that have the potential to assist towards the long-term evaluation and validation of these games' impact. Hence, future developments in the field will feature "integrated gaming", fusing data from games and social networks with personal data, and providing feedback to diagnostic systems (McCallum, 2012). Obviously, all the issues that have been previously discussed regarding ethics and privacy are of paramount importance in this context.

5.2.3. Ambient Assisted Living

A well-known domain pioneering in assisting a person's living conditions, aimed at supporting older and disabled users, is AAL. AAL refers to the use of ICT in a person's living environment, to improve their quality of life and enable them to stay independent and active for as long as possible (Moschetti, Fiorini, Aquilano, Cavallo, & Dario, 2014; see also Section 5 for a discussion on technologies to support the disabled and the aging population). AAL, which is rooted in Assistive Technologies and "Design for All" approaches (Pieper, Antona, & Cortés, 2011) and has emerged as a technological response to the phenomenon of population aging, benefits from the AmI computing paradigm to provide intelligent, unobtrusive, and ubiquitous assistance (Blackman et al., 2016).

The main solutions conceived to support older people in need of care fall into three main AAL service areas: prevention; compensation and support; as well as independent and active living. Indicative services include the prevention of early degeneration of cognitive abilities, promotion of healthy living lifestyle, management of chronic diseases, fall prevention, management of daily activities, maintaining social contacts, and having fun (Blackman et al., 2016; Moschetti et al., 2014). Such environments can often be equipped with robotic systems for assisting older adults in daily activities, such as cleaning, picking up things, as well as in their mobility. However, they can also contribute to the social, emotional, and relational aspects of older adults' lives. (Breazeal, Ostrowski, Singh, & Park, 2019). Future efforts should focus on person-centered care, by improving personalization of care, and considering different needs, expectations, and preferences of individuals (Kachouie, Sedighadeli, Khosla, & Chu, 2014).

Given the technical capabilities of AAL environments, and their potential for recording personal and sensitive data implicitly and explicitly, privacy and ethics (see also Section 4) are dominant concerns. Privacy and confidentiality should be safeguarded, while technology should not replace human care, resulting in older adults' isolation (Rashidi & Mihailidis, 2013), nor should it lead to abuse and violation of human rights (*e.g.* excessive control by caregivers).

5.2.4. Intelligence in healthcare

With the advent of IoT and environment intelligence, it has been foreseen that the traditional professional-centric model of healthcare will transform into a distributed healthcare system, where the individual becomes an active partner in the care process (Arnrich et al., 2010). Intelligent environments have the technological infrastructure and ability to support this transformation. In particular, they are substantially adept at discovering patterns, detecting anomalies and deviations from daily routines (*e.g.* indicating an imminent health problem or a crisis that needs to be attended to), as well planning and scheduling (Acampora, Cook, Rashidi, & Vasilakos, 2013; Consel & Kaye, 2019). An important potential pitfall refers to overreliance on the technology, which may tamper with individuals' self-confidence to manage their life and result in preliminary loss of abilities (Acampora et al., 2013). Moreover, overreliance can also lead to patient isolation and loss of personal care (Acampora et al., 2013; Andrade et al., 2014) (see also Section 4.2.3).

Intelligent environments for healthcare also extend to environments for therapy and rehabilitation, as well as smart hospitals in the support of medical staff (Acampora et al., 2013). Intelligence may include AI techniques, which are used in healthcare and medicine. Typically, the AI methods employed are machine learning, expert systems, and knowledge representation techniques which are mainly exploited in the context of diagnosis, prognosis, and medical training (Acampora et al., 2013). However, new potentials emerge through the evolution of deep learning methods, achieving high accuracy and performance comparable to that of experienced physicians (Jiang et al., 2017). This evolution does not imply that technology will substitute humans; instead, it suggests that it can effectively support them by taking care of trivial tasks, empowering humans towards enhanced performance and attainment of higher goals. Robots and autonomous agents can also constitute a component of an intelligent environment in the context of healthcare. In brief, robots for healthcare can be classified as inside the body (*e.g.* surgical robotics), on the body (*e.g.* prosthetics), and outside the body (*e.g.* robots for physical task assistance, robots as patient simulators, or care robots) (Riek, 2017). Two challenging issues for the adoption of robotics in healthcare are their acceptance by end-users, as well as their high cost, which is still prohibitive (Andrade et al., 2014). User acceptance in the case of robots is determined not only by usability factors, but also by the robot's form and function (Riek, 2017). In the case of intelligence and robots used to support clinical practices, the medical staff (physicians and nurses) also confronts the danger of becoming over-dependent on technology. This highlights again the need for addressing ethical concerns and designing technological environments that bring to the forefront human values and autonomy.

Future research in the field should focus on pervasive, continuous and reliable long-term sensing and monitoring (Arnrich et al., 2010). Safety and reliability are also key requirements to address in the context of healthcare robotics (Riek, 2017). This will result in reliable and trustworthy systems that can be accepted both by patients and doctors. In addition, research should focus on developing new and evolving existing design and evaluation methods for ubiquitous patient-centric technologies (Arnrich et al., 2010), where evaluation should move beyond classical HCI aspects to healthcare aspects, as well as to the long-term impact of these technologies on patients' quality of life. Moreover, the assessment of the clinical effectiveness of clinical intelligent systems and robots constitutes a key factor for their adoption in the healthcare domain (Riek, 2017).

Predictions for the future of the field identify that "health-enabling and ambient assistive technologies will not even be recognized as such; they will be an integrated part of the health system" (Haux et al., 2016). By using big data, IoT, and AI, it will be possible to collect data for a wide number of medical issues stemming from a wide variety of contexts and train AI models that will be able to predict, diagnose, and even suggest appropriate treatments. In this respect, two main issues arise: data privacy and ethics, as well as the assessment of the performance of intelligent environments. With regard to the latter, it is crucial to identify the impact that any misjudgments of the technological environment may have on the individual, and to realize that any technological failures will no longer be as "innocent" as in the past. They will entail risks not only for users' work or leisure activities, but also for their health, well-being, and even their life. This realization opens a breadth of discussions regarding the education and training of designers and software engineers, the development of an ethical code, as well as the establishment of novel evaluation and testing procedures.

5.2.5. Well-being and eudaimonia

Beyond physical health, self-tracking and ICT in general have been used to pursue mental health (Thieme, Wallace, Meyer, & Olivier, 2015) and mood regulation (Desmet, 2015), in the wider context of technology for user eudaimonia and happiness. Aligned with this approach is the concept of positive computing, which aims to develop technologies to support well-being and human potential for individuals with diagnosed mental health conditions, but also for anyone through preventative mental health support, strengthening mental health through positive behavior change and self-reflection, and through increasing empathy towards and awareness of mental health (Wilson, Draper, Brereton, & Johnson, 2017). Assisted by the advancement that UX has brought by encompassing emotional and more pleasure-oriented aspects, and by positive psychology that advocates positive human development, positive design offers the framework for pursuing the design of technologies for lasting wellbeing by targeting eudemonic experiences of products, services, and of the activities they enable (Pohlmeyer, 2013).

A major concern in the direction of technology for well-being and eudaimonia is that – at least for the time being – this partnership between positive psychology and interactive technology is mainly on a conceptual level (Diefenbach, 2018). In the new era, HCI will need to change focus, shifting from user experience to user eudaimonia, studying how technology ensures users' well-being. This is a challenging undertaking, in principal due to the inherent difficulty entailed in defining and measuring these concepts (Gilhooly, Gilhooly, & Jones, 2009). In addition, in contrast to physical well-being, human eudaimonia is entirely subjective and therefore a challenging target to analyze, model, and address through technology. Reflecting back to topics discussed in the previous three challenges (Section 2, Section 3, and Section 4), it is evident that in order to effectively and efficiently support people in their pursuit of happiness, well-being, and eudaimonia, a harmonious symbiosis of technology and humans is required, featuring humane intelligence and respecting human rights.

In addition, despite any advances in the field of technology for well-being, an open research question that needs to be resolved in order to develop technologies that will demonstrably advance the well-being of humanity is the lack of concise and useful indicators to measure those advancements (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019). Such metrics should take into account not only individual and community well-being, but also environmental and planet goodness (see also Section 7), as well as human rights, capabilities, and fair labor, as these circumstances among others constitute the basis for human well-being (The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems, 2019).

5.3. Summary of emerging requirements

Overall, technology in the context of healthcare is already widely used, for instance through personal medical and self-tracking devices, serious games, and AAL environments. More advanced technologies, such as AAL and intelligent environments, featuring AI and robotics, have already seen their application in the field, yet there are still open research issues. Beyond physical health, technology can also be used to promote human well-being, including not only health aspects, but also psychological well-being through life goals' fulfilment, by helping to prevent, reduce and manage stress, depression and psychiatric illness, as well as by fostering purposefulness, self-confidence, and positive feelings. Table 5 lists a summary of the challenges entailed, as they have been highlighted throughout this section.

6. Accessibility and universal access

6.1. Definitions and rationale

Accessibility of Information Technology (IT) is a topic that has actively engaged the HCI research community, and which aims to ensure that IT applications and services can be used on an equal basis by users with disabilities and older users. First efforts in the field pursued accessibility via a posteriori adaptation, that is, by employing assistive technologies to provide access to applications that were originally designed and developed for non-disabled users (Emiliani & Stephanidis, 2005). The reactive nature of these approaches has been criticized for its failure to catch up with the fast pace with which technology evolves, for its cost-ineffectiveness, as well as for the fact that it cannot always ensure equal access without functionality loss (Stephanidis & Emiliani, 1999).

This criticism stimulated the conceptualization of theories, methodologies, and tools of a proactive and more generic nature that could more accurately adapt to the increased interactivity of new technologies. Universal access advocates the right of all citizens, regardless of age and disability, to obtain equitable access to, and maintain effective interaction with, IT information resources and artifacts (Stephanidis et al., 1998). In the context of universal access, design for all has been defined as a general framework catering for conscious and systematic efforts to proactively apply principles, methods, and tools to develop IT products and services accessible and usable by all citizens, thus avoiding the need for a posteriori adaptation, or specialized design. Indicative of the importance and interest that this area has received is the number of relevant terms and approaches used to describe the notion of proactive solutions to accessibility, comprising inclusive design, barrier-free design, universal design, and accessible design (Persson, Åhman, Yngling, & Gulliksen, 2015).

Two decades later, and in view of the technologically enriched environments that have already pervaded and the intelligent environments that are about to be materialized, several questions arise. Have the aforementioned approaches been fruitful? How can the knowledge and experience acquired from these past approaches be applied to the new technological environments? What are the promises and challenges that these new environments bring with regard to universal access? This section attempts to provide insights to these inquiries.

6.2. Main research issues and state of the art

6.2.1. Adoption of proactive approaches

Accessibility has been established in national legislation and is also employed by international standardization organizations, which signifies that on a political level it is not only of importance for people with disabilities, but anyone can also benefit from universal access approaches, as it is now clear that one's abilities are constantly changing (Persson et al., 2015). Yet, it is a fact that industry – at large – has not embraced proactive approaches.

A potential reason that has been identified early is that although the total number of older or disabled persons is large, each individual disability or impairment area represents only a small portion of the population, therefore it would be impractical and impossible to design everything so that it is accessible by everyone regardless of their limitations (Vanderheiden, 1990). On the other hand, the range of human abilities and the range of situations or limitations that users may find themselves in is too large; therefore, products could only focus on being as flexible as commercially practical (Vanderheiden, 2000).

Proactive approaches do not advocate a "one-size-fits-all" approach; instead they aim to promote accessibility for everyone through the adaptation of the design to each user. As a result, many companies perceive universal design as an extra

Table 5. Challenges for technology supporting well-being, health, and eudaimonia.

Main Issues	Challenges
Personal Medical Devices and self-tracking	• Acceptance by the medical community • Reliability of devices • High potential for misinterpretations, when patients without medical training attempt to interpret symptoms based on PMD data • Integrated analytics, effectively combining data from various sources • Ethical concerns for persuasive strategies • Loss of human free agency and autonomy • Privacy and autonomy threats (humans are under surveillance and discipline) • Ethical concerns regarding the usage of the generated data • Sociological concerns regarding quantified bodies • Scientific accuracy and objectivity of self-tracking activities • Inadequacy of numbers to represent the complexity of human nature
Serious games for health	• Limited adoption of serious games for health • High design and development complexity leading to slow speed of implementation • Demanding user expectations, which are formed by the entertainment industry • High cost *vs*. undeveloped market • Evaluation of the actual impact of serious games on the individuals' health
Ambient Assisted Living	• Privacy and confidentiality • Replacement of human care by technology • Isolation of the older adults and patients • Excessive control by caregivers, leading to violation of human rights
Intelligence in healthcare	• Over-reliance on the intelligent environment, leading to preliminary loss of abilities • Patient isolation and loss of personal care • Over-dependence of the medical staff on technology • Safety and reliability • Accuracy • Clinical effectiveness assessment of medical technologies • Long-term evaluation of the impact of these technologies on patients' quality of life • New design and evaluation methodologies for patient-centric design • New development and testing procedures ensuring the accuracy of technologies, eliminating risks for the patients' well-being and life
Well-being and eudaimonia	• Difficulty in defining and measuring well-being and eudaimonia • Subjective nature of these concepts, impeding their analysis and modelling • Broad scope of the concepts extending beyond the individual to community well-being and planet goodness, as well as other concepts, such as human rights and fair labor

cost or an extra feature, a perception, however, which is not accurate (Meiselwitz, Wentz, & Lazar, 2010). On the contrary, by adopting a universal access approach, companies could achieve a number of business-oriented objectives, including to increase market share, take market leadership, enter new product markets, achieve technology leadership, and improve customer satisfaction (Dong, Keates, & Clarkson, 2004).

Overall, proactive approaches do not propose the elimination of assistive technologies. Such technologies have always been a good solution to many problems of individuals with disabilities. Besides representing a societal need, assistive technologies constitute a notable niche market opportunity (Vanderheiden, 2000), and according to current market predictions assistive technologies are even expected to experience some growth (Rouse & McBride, 2019). Nevertheless, as technology evolves and taking into account the frequent comorbidity of disabilities (especially in the case of older adults), proactive approaches can become a more realistic and plausible solution in the near future (Stephanidis & Emiliani, 1999).

6.2.2. Population aging

In view of the technologically enriched environments where all citizens will have to live, the approach of adapting already developed technologies as a solution to the problems of integration of people with disabilities, will not be tenable (Emiliani, 2006). An important influential factor is the rapid aging of population, resulting in a considerable proportion of the future technological environments users being elder, who – in a literal sense – perceive technology differently, due to functional limitations and age-related changes in cognitive processes (Charness & Boot, 2009; Czaja & Lee, 2007). Within this perspective, universal access in the new technologically-enriched environments constitutes a challenge with renewed and increased interest, where open issues need to be promptly explored.

Moreover, the rapid aging of the population requires appropriate approaches for "aging in place", that is remaining active in homes and communities for as long as possible, avoiding residential care, and maintaining independence, autonomy, and social connectedness (Pfeil, Arjan, & Zaphiris, 2009; Wiles, Leibing, Guberman, Reeve, & Allen, 2012). AAL environments (see also Section 5.2.3) have the potential to support independence and quality of life of older adults (Blackman et al., 2016). Assisted living systems can also contribute in addressing emergency situations, which are expected to note a dramatic increase due to the aging of the population and the consequent rise of chronic diseases (Kleinberger, Becker, Ras, Holzinger, & Müller, 2007). At the same time, following a similar strategy, ambient assisted working can foster adaptations of the workplace, thus ensuring that the aging and disabled population are active and participate for the longest possible in the workforce (Bühler, 2009). Besides living and working environments, it is necessary that public environments and especially transportation systems are revisited and redesigned in order to be age-friendly and age-ready (Coughlin & Brady, 2019). Overall, a major concern is how elder users will be motivated to use ICT technologies and how acceptable they will find them, factors which are both expected to go through changes in the near future, as a new generation of technologically-adept elder users will emerge (Vassli & Farshchian, 2018).

6.2.3. Accessibility in technologically enriched environments

These new environments bring about several risks, yet they also bear the potential to effectively address old and new accessibility issues and requirements, due to their technological richness. In particular, the abundance of interactive and distributed devices can result in a relaxed and enjoyable interaction, employing multimodal interfaces, thus providing for each user those interaction modes that are more natural and suitable (Burzagli, Emiliani, & Gabbanini, 2007). Other benefits ensured by these new environments include the possibility of task delegation to the environment and its agents, which can reduce physical and cognitive strain, as well as the breadth of applications and services that will be available, addressing a wide variety of domains that are critical for the disabled and older users. Henceforth, a fundamental benefit of these environments is that they will be able to further support independent living, and provide higher quality of healthcare, aligned with the AAL vision to solve problems caused by the aging of the population (Stephanidis, Antona, & Grammenos, 2007).

Despite their inherent assets, several matters pertaining to universal access that mainly stem from the environments' increased technological complexity, need to be resolved. For instance, it has been identified that the use of "natural" interaction techniques, through spoken commands and gestures, may actually "ban" users with disabilities and that spoken communication from the environment, or complex messages in large mural screens or in small wearable displays may be prohibitive for some users (Abascal, De Castro, Lafuente, & Cia, 2008). Moreover, the multitude of devices, applications, and environment intelligence can impose high cognitive demands on users, if not properly designed. This complexity is further increased by the fact that technology "disappears" in the environment and interaction becomes implicit (Streitz, 2007). Another cause of complexity refers to the potential of the environment to make decisions and learn from users' behavior. As already discussed in Section 2.2.1, intelligent environments need to be transparent to their users, however this constitutes a new accessibility challenge on its own, especially for older people and individuals with cognitive disabilities. Moreover, complexity is also induced by the increased involvement and interaction with digital artifacts that will be in abundance. In this context, the challenge for intelligent environments is to not be too interaction intensive, despite the fact that humans will be surrounded by a wide range of computing devices of different functionality and scale. Another important concern pertains to the different levels of accessibility that need to be ensured: accessibility of the individual devices for their owners and potentially other users with different requirements, accessibility of the environment as a whole (devices, content, and functions provided), as well as the combination of accessibility of the virtual and physical world. Finally, ethical issues (Section 4), as well as issues related to the symbiosis of human and technology (Section 2), are obviously of utmost significance.

6.2.4. Methods, techniques, and tools

Strategies followed for the development of Assistive Technologies will no longer be appropriate in the context of component-based, distributed technological environments (Treviranus, Clark, Mitchell, & Vanderheiden, 2014). Taking into account past knowledge and experience, as well as the opportunities and difficulties inherent in technologically enriched environments, it is evident that several research directions need to be explored. Understanding the evolving human needs and context of use, developing appropriate user models (Casas et al., 2008), as well as advancing knowledge of user requirements and of the appropriateness of the various solutions for the different combinations of user and environment characteristics (Margetis, Antona, Ntoa, & Stephanidis, 2012) constitutes a path that should be explored. The development of appropriate architectures, ready-to-use accessibility solutions, and appropriate tools are also essential elements of pursuing universal accessibility in technologically enriched environments (Margetis et al., 2012; Smirek, Zimmermann, & Ziegler, 2014). Automatic generation of accessible user interfaces is another research direction worth exploring for its potential to create accessible personalized interfaces (Jordan & Vanderheiden, 2017). Finally, new evaluation methodologies and tools need to be targeted, so that all the aspects of a user's experience (including accessibility) in such environments are assessed, way beyond usability and UX assessment in typical evaluation setups.

6.2.5. Universal access in future technological environments

Forthcoming technological environments will not be simply the smart home or workplace, but entire smart cities, such as the "Humane, Sociable and Cooperative" hybrid cities envisioned by Streitz (2011). Taking into account that technology will be a vital component of any daily activity and it will cater for humans' needs, prosperity, and well-being (see Section 4.3), the stake for universal access is now much higher than in the past.

Particular attention needs to be paid to any individual at risk of exclusion, so that the new futures do not exclude, isolate, or exploit anyone (Chatterton & Newmarch, 2017). Research has identified several factors that have an impact on digital inequality, including race and ethnicity, gender, and socioeconomic status (Robinson et al., 2015). Other influential factors include age, education, occupational status, health, social connectedness, and availability of infrastructures (*e.g.* people in rural areas have lower levels of access to high-quality internet connections) (Van Deursen & Helsper, 2015). Further elaborating on the causes of the digital divide is a subject of social science research and beyond the scope of this paper. Whatever the reasons for which individuals may be at risk of exclusion, the challenge is that universal access becomes a matter of paramount importance in the forthcoming future, when access to technology will not only mean access to information but to well-being and eudaimonia (see also Section 4.3).

6.3. Summary of emerging requirements

In summary, as HCI has always focused on the human, in the new technology-augmented environments, efforts in the field will be extended towards improving the quality of life of various populations, including the disabled and older persons. Accessibility and Universal Access are not new concepts, however in view of the population that is aging and of the constantly increasing technological complexity, they become not only timely, but also pivotal for the prosperity of future societies. Undoubtedly, the advent of intelligent environments entails universal access risks (see Table 6), nonetheless it also offers new opportunities that should be exploited. What is certain though, is that reactive approaches to accessibility will fail at addressing the inherent complexity and scalability requirements of future interactive environments. The requirement for more holistic approaches becomes now more prominent than ever, constituting a near-future research direction for the HCI field.

7. Learning and creativity

7.1. Definitions and rationale

As technologies continue to mature, new opportunities for fostering individual growth through multimodal stimulation of how humans learn and apply creativity will emerge. People with diverse backgrounds, skills, and interests will be able to collaborate to solve challenging problems, by cooperatively learning and creating knowledge together. In this new era, technology will support and promote new learning styles, multimodal learning affordances, as well as lifelong learning. This flexibility encourages, nurtures, and amplifies human creative skills in fields such as arts, science, and design. At the same time, the discussion of how technology should be applied in the learning context has become timelier than ever, expanding to issues such as privacy and ethics, learning theories and models, and pedagogical aspects.

Learning assisted, enhanced and mediated by technology is not a new concept, and many types of technologies are already used in schools today. Hardware includes computers, projectors, interactive whiteboards, and smart mobile devices, while software involves office applications (*e.g.* word processors and presentation tools), online learning management systems, social networking sites and applications, online encyclopedias and search engines, communication software, as well as serious games (De Gloria, Bellotti, & Berta, 2014; Ng, 2015; Spector, Merrill, Elen, & Bishop, 2014). The contribution of ICT in education supports the sharing of material and teaching tasks, while also enhancing connectivity, cooperative work, and expands experiential learning opportunities outside of the classroom (Augusto, 2009). In addition, it has been argued that digital technologies: (i) support learning by increasing students' motivation, providing demonstrations of the topics taught and adapting to each student's individual pace; (ii) contribute to the development of the so called twenty-first century skills, such as

Table 6. Accessibility and Universal Access challenges for technologically enriched environments.

Main Issues	Challenges
Adoption of proactive approaches	• Industry reluctance due to a number of reasons: niche market, commercial practicality of addressing a wide range of human abilities, and cost
Population aging	• Users perceive (in a literal sense) technology differently • Aging in place • Increased incidence of emergency situations • Active participation in the workforce • Age-friendly and age-ready public environments and transportation systems
Accessibility in technologically enriched environments	• Inadequacy of reactive approaches in the context of distributed technological environments • Exploitation of the technological infrastructure and multimodality offered • Natural interaction techniques may be prohibitive for some users • High cognitive demands imposed on users due to the technological complexity of the environment, implicit interactions, and the need for AI transparency • Different levels of accessibility: accessibility of systems for their owners and potentially other users with different requirements, accessibility of the environment as a whole (devices, content, and functions provided), as well as the combination of accessibility of the virtual and physical world
Methods, techniques, and tools	• Advancement of knowledge regarding human needs and context of use in technologically enriched environments • Development of appropriate user models • Analysis and classification of the of the appropriateness of the various solutions for the different combinations of user and environment characteristics • Development of appropriate architectures for universal accessibility in technologically enriched environments • Development of ready-to-use accessibility solutions • Automatic generation of accessible user interfaces • New evaluation methodologies
Universal Access in future technological environments	• Technology will be a vital component of any daily activity • Intelligent environments will cater for humans' needs, prosperity, and well-being • Digital inequality and lack of universal access will not only pertain to access to information, but also to humans' health, well-being, and eudaimonia

communication, collaboration, problem-solving, critical and creative thinking; and (iii) foster the development of digital citizenship and lifelong learning (Ng, 2015).

Research has also debated customary educational approaches and advocated that technology can now support varying learning styles and approaches, be it situated learning, authentic learning, or ubiquitous learning. Situated learning argues that learning occurs from our experience of participating in daily life and is shaped by the activity, context and culture in which it occurs (Lave & Wenger, 1991). Authentic learning, requires students to address real-world problems in contexts that mimic the work of professionals, and is typically associated with the apprenticeship model in traditional educational paradigms (Burden & Kearney, 2016). Ubiquitous learning, empowered by mobile technology, stands for learning anywhere and at any time (Hwang & Tsai, 2011). All these approaches promote learning beyond the typical classroom boundaries, a potential that can liberate education towards new directions. After all, if civilization were to invent higher education today, rather than centuries ago, it is not at all certain if campuses would be dominated by lecture rooms, libraries, and labs, or if learning would be organized in fixed time blocks (Dede, 2005).

This section discusses the main issues regarding the use of technology for learning and creativity, as they are shaped by the advent of new technologies and are expected to be influenced by intelligent environments. Its focus is to highlight the unique contributions of each technology to learning and to discuss challenges and implications from the use of technology in learning.

7.2. Main research issues and state of the art

7.2.1. A new generation of learners

Besides technology advancements, it has been claimed that students' interaction with learning materials has changed. Neo-millennials, digital natives, or Generation Z, a generation whose world was shaped by the Internet and who are fluent technology users (Seemiller & Grace, 2016), show different learning styles than previous learners. For neo-millennials, learning is characterized by seeking and synthesizing, rather than by assimilating a single "validated" source of knowledge (*e.g.* books, lectures), multitasking is the norm, and personalization is pursued (Dede, 2005). Other attributes of neo-millennials are that they prefer active learning based on experience (real and simulated), and co-designing of learning experiences (Dede, 2005). But there is also the danger that students prefer a "copy and paste" attitude, exploiting the wide range of information available on the web (Comas, Sureda, & Santos, 2006), instead of actually creating new content or drawing new inferences. There are two aspects to it: (i) students might use wrong information, because not all sources on the web are equally trustworthy, and (ii) it may encourage a tendency to plagiarism, which is a big problem so that special software had to be developed to identify plagiarism.

Although it seems evident that technological pervasiveness has and will influence humans in multiple levels, including learning styles and behaviors, we should be careful in our generalizations. The aforementioned characteristics of young learners are apparently true for some of them (few or many – it doesn't matter), yet they are not valid for every learner (Bennett, Maton, & Kervin, 2008). As a result, technological developments in the field of learning should not adopt any such generalizations and assume that all new learners are technologically adept or that they exhibit specific behaviors and preferences. New technologies can certainly accommodate new and emerging learning styles, providing additional functionalities and tools to support tutors and learners. However, they should keep the human at the center and study the various needs and requirements of each individual, avoiding the assumption that there is an "average learner"; instead they should support personalized learning and adaptation to each individual learner. Therefore, there is a need to understand the influences of human factors in order to design digital learning environments that best suit each and every learner (Chen & Wang, 2019).

7.2.2. Extended reality

Extended reality technologies (*i.e.*, VR, AR, and Mixed Reality (MR)) offer the opportunity for blending the digital world with the physical, in a multimodal interactive fashion that can personalize and elevate the learner's experience (Kidd & Crompton, 2016) (see also Section 3.2.5 for a discussion of the interaction-related challenges in VR and AR environments). Several benefits have been reported for the use of these technologies in learning. An important advantage refers to their power to visualize complex and abstract concepts (*e.g.* airflow of magnetic fields, chemical reactions), as well as to support hands-on experiences with places that could not be visited (*e.g.* a historical site) (Akçayır, Akçayır, Pektaş, & Ocak, 2016; Lee & Wong, 2008). Additionally, as an interactive technology medium, extended reality has the potential to create stimulating experiences and increase learners' motivation, support collaboration between students, and foster student creativity and imagination (Yuen, Yaoyuneyong, & Johnson, 2011).

The use of extended reality technologies in learning may also interfere with learning and pedagogical goals, for example by detracting students' attention to the technology itself, or by altering learning to accommodate for technology limitations (FitzGerald et al., 2013). An additional concern refers to the ease of use of the extended reality environment for learners and tutors. For example, a common difficulty that learners encounter in VR environments is navigation using a 3D interface, while creating educational content in an extended reality environment can be a cumbersome task (Huang, Rauch, & Liaw, 2010; Yuen et al., 2011). Hence, a challenging aspect for the design of these technologies is how to employ them in order to appropriately support the entire educational process, from the design of the content to the delivery of the learning experience. Apparently, this requires a multi-disciplinary approach and the active engagement of tutors, not merely as providers of educational content, but as users of these technologies and knowledge conveyors.

7.2.3. Mobile learning

Mobile devices are often used in the context of AR applications, but also in a wider learning context, promoting situated, authentic, and ubiquitous learning. Mobile devices' suitability towards the aforementioned learning approaches mainly stems from their characteristics, and namely portability, connectedness and social interactivity, context sensitivity, and individuality – as personal devices can fully support customization and personalization (Naismith, Lonsdale, Vavoula, & Sharples, 2004).

Users are already familiar with mobile devices, henceforth challenges mostly refer to how mobile technologies can be effectively and efficiently employed in learning. Incorporating mobile technologies in education raises concerns as to how learning activities should be designed by instructors and how educators' and learners' thinking is reconceptualized when mobile devices are used seamlessly across the "traditional boundaries between formal and informal contexts, virtual and physical worlds and planned and emergent spaces" (Burden & Kearney, 2016). A major concern is that although several qualitative studies report positive results regarding mobile learning and its relevance with new learning approaches, there is a notable lack of quantitative reports on long-term impact (Pimmer, Mateescu, & Gröhbiel, 2016). In any case, the full potential of mobile learning will be reached when technological developments intersect with ongoing educational trends, and when learning experiences are truly mobile (Pegrum, 2016). As Naismith *et al.* put it, "the success of learning and teaching with mobile technologies will be measured by how seamlessly it weaves itself into our daily lives, with the greatest success paradoxically occurring at the point where we don't recognize it as learning at all" (*p*. 36).

7.2.4. Serious games for learning

Several studies have discussed the positive impact of games in the learning context. Positive effects include the high engagement of players, the presentation of complex notions and experiences, the collaboration among learners, the facilitation of deep understanding, as well as the connection with young learners' dispositions and orientations (Beavis, 2017). Other benefits include the enhanced cognitive, skill-based, and affective outcomes that are achieved through games used for education and training (Wilson et al., 2009). Despite claims however, real evidence from long-term studies on the educational impact of games is scarce (Bellotti, Berta, & De Gloria, 2010).

An important concern in the field is how to design for and how to measure fun in the user experience of serious games (Raybourn & Bos, 2005). The right balance between seriousness and gamification needs to be found: if too much educational content prevails, learners' motivation may decrease; on the contrary, if too much fun is incorporated, this can undermine learning (Gros, 2017). There are several questions that remain to be answered regarding serious games for education, which all highlight the need for deepening our understanding in the field. In this respect, design processes, metrics and evaluation tools focusing on the assessment of students' learning progress need to be developed (Bellotti et al., 2010). In these activities, all stakeholders (including teachers, policymakers, and parents, as well as commercial game companies and educational researchers) should be involved and collaborate, so as to ensure that game objectives and learning objectives are aligned (Young et al., 2012).

7.2.5. Intelligent environments

The technological fabric of smart environments, AI, and big data has made possible the realization of scenarios that might seem fictional a few decades ago. Big data, and in particular the availability of very large data sets from students' interactions with educational software and online learning, constitutes the basis for the evolution of two research fields, namely learning analytics and educational data mining (Konomi et al., 2018; Siemens & Baker, 2012). The potential application areas for these fields include supporting instructors through appropriate feedback, providing recommendations to students, predicting students' performance, detecting undesirable student behaviors, grouping students (according to personal characteristics or preferences), offering pedagogical support, or developing concept maps (Romero & Ventura, 2010). Advances in analytics can be used in the context of Intelligent Tutoring Systems (ITS) or smart learning environments. ITSs provide individualized instruction and have the potential for significantly higher achievement outcomes than other modes of instruction (except small-group human tutoring and individual human tutoring when results were comparable) (Ma, Adesope, Nesbit, & Liu, 2014).

Smart environments for learning may well support context-aware and ubiquitous learning, by identifying learners' context and providing integrated, interoperable, pervasive, and seamless learning experiences (Mikulecký, 2012). In such environments, learning can be viewed as a lifetime process that happens whenever and wherever the learner chooses, in a collaborative and self-paced style (Mikulecký, 2012), and by supporting multi-generational and co-creational learning activities (Konomi et al., 2018). Under this perspective, the concept of self-regulated learning – according to which the learners are active participants who monitor and apply strategies to control their learning process – is highly relevant with the notion of technological intelligence (Guerra, Hosseini, Somyurek, & Brusilovsky, 2016). In ubiquitous learning environments, a major challenge is how to provide learners with the right material at the right time and in the right way, especially taking into account that when many users are involved in such environments, the decisions of one can be affected by the desires of others (Mikulecký, 2012). From the teachers' viewpoint, one of the most important difficulties that needs to be faced is how teachers can keep track of the learning activities in progress, as in technologically-complex and ubiquitous educational settings activities frequently involve a number of separate groups of students interacting simultaneously from distant locations using different technologies (Muñoz-Cristóbal et al., 2018).

Smart classrooms, on the other hand, are closely related with formal education. They pertain to educational environments equipped with smartness, therefore capable of detecting underperforming students, and providing advice and recommendations on how to better support them. Other smart classroom functional characteristics include that they can profile students according to their activity and tailor educational material, automatically identify students, and provide reminders and advice to each student according to their goals, activities, and performance (Augusto, 2009). In such environments, the technological infrastructure makes it possible to perceive undesired behaviors such as mind wandering (Bixler & D'Mello, 2016) and also to detect affect through interaction data, facial expressions, and body posture, in order to identify off-task behavior and provide encouragement or stimulate the students' interest through alternative learning materials (Bosch et al., 2015).

In brief, the technological infrastructure and advances in fields such as big data and AI give the opportunity for monitoring the learning environment and the learners, delivering adapted and personalized instruction, tracking affect and undesired behaviors, and proposing solutions to tackle them. However, the main challenge is not what technology can do; instead it is if it should do it and how. For instance, a common student behavior that is criticized and attempted to be tackled through technology is mind wandering; however, recent studies have shown that mind wandering may play a crucial role in a person's life planning and creative problem solving (Mooneyham & Schooler, 2013). Furthermore, not every experimental finding on mind wandering can be generalized over every person and situation, as self-generated thought is a process that depends on multiple cognitive processes, on an individual's profile of affective traits, cognitive ability, or motivation (Smallwood & Andrews-Hanna, 2013). In a nutshell, the enhanced monitoring capabilities raise concerns regarding ethics, privacy and human rights. Do students (and their parents) trust the privacy levels of a system that in order to provide personalized learning demands to record data from them, access their notes and requires a more open connectivity with peers and tutors (Augusto, 2009)? Who is the owner of the data collected and what rights do learners have with regard to their personal data (Ferguson, 2012)? How acceptable and ethical it is to monitor users, especially in the case of underage individuals? How can excessive control (by the technological environment, educators or parents) be avoided? How can/should persuasive technologies be incorporated into learning environments (Marcus, 2015b)? Last but not least in this series of questions, do excessive monitoring and classroom statistics serve existing and tangible educational needs of instructors and learners (*e.g.* do instructors actually need a system to tell them when a student's mind is wandering)? The new learning technologies should not only support the acquisition of knowledge, but also enhance human learning abilities. New technologies are often applied to make learning as easy as possible. By doing so, they inadvertently make learners more dependent on technologies. The challenge is how to improve human learning abilities while trying to make learning effective and effortless.

7.2.6. Pedagogical impact of learning technologies

A big proportion of issues that are still open for discussion refers to the pedagogical impact of these technologies and the role of human tutors. A major concern is that technology should focus on the perspectives and needs of learners themselves and push the boundaries of education towards other criteria beyond grades, such as motivation, confidence, enjoyment, satisfaction, and meeting career goals (Ferguson, 2012). It is also important to first consider what the learning goals of an educator are before considering how to achieve any specific learning objectives through technology, and to admit that in certain cases there may exist other more efficient, appropriate and resilient means to achieve it without the involvement of technology (FitzGerald et al., 2013). Another challenge to the effective pedagogical use of technology in education is that in different economic, social, and cultural environments, the same technology may perform differently (Spector et al., 2014); therefore, a "one solution to fit all" approach would not be viable, and technology should be customizable and adaptable. More importantly, in order to mark real progress in the field and deliver technologies that address existing problems of the educational process, educators themselves should be extensively involved in the development of relevant technology (Spector et al., 2014).

7.2.7. Creativity

Recently, a discussion that has been stimulated by a large part of the society (artists, writers, teachers, psychologists, and philosophers) refers to the lack of creativity in educational curricula (Loveless, 2007). Research on creativity identifies two trends: the "big C" creativity of the genius, where the achievements are unique, excelling, and novel, and the "little C" creativity, which can be defined as a behavioral and mental attitude or the ability to find new and effective solutions to everyday problems (Ferrari, Cachia, & Punie, 2009). Although the first type of creativity is very important for humanity, this discussion refers to the second type of creativity which does not address only a few gifted and extraordinary individuals, but everyone. This type of creativity not only depends on education and training, but it can also be fun, involves play and discovery, and requires hard work, good field knowledge and the development of thinking skills (Ferrari et al., 2009).

Creativity and learning are therefore two strongly associated concepts that have shaped the notion of creative learning, which should be pursued in the context of current and future education curricula, and is aligned with the so-called twenty-first century skills. Creative learning refers to any learning that is learner-centered and involves understanding and new awareness, which allows the learner to go beyond knowledge acquisition, and focuses on thinking skills (Cachia, Ferrari, Ala-Mutka, & Punie, 2010). Creative learning can be achieved by appropriately designed educational environments, activities and teaching practices, while it can be supported by the use of digital technologies in education (Ferrari et al., 2009; Loveless, 2007). For instance, digital technologies can be used in the context of creative learning to develop ideas, to facilitate connections with other people, projects, information and resources, to collaborate and co-create, as well as to present and promote one's work (Loveless, 2007). A relevant concept is that of creative classrooms which constitute live eco--systems that emphasize the need to develop and assess skills beyond factual knowledge, numeracy and literacy, such as problem-finding, problem-solving, and collaboration (Bocconi, Kampylis, & Punie, 2012). Such classrooms also value both formal and informal learning, and give opportunities for creative and personalized learning. Overall, creative learning, creative classrooms, and the support for creativity in education is totally aligned with the notion of ubiquitous learning and can be fully supported by the use of new technologies. An important concern regarding creativity in educational environments is that creativity goes beyond the "I-paradigm" to the "We-paradigm" (Glăveanu, 2018), therefore technology should not focus only on the individual learner. It should consider learners as creative actors that collaborate within the learning environment and explore how they can be supported (Glăveanu, Ness, Wasson, & Lubart, 2019).

Beyond the learning context, human creativity is expected to have a central role in the forthcoming intelligent era, while it has been claimed that creativity, imagination, and innovation are three key resources of the humankind that will assist in facing some of its most daunting challenges (Robinson, 2011). Therefore, it is important to not only cultivate it, but also explore how it can be assisted. Creativity support tools aim to assist users and extend their capabilities in making discoveries or inventions from the first stages of the creation process (information gathering and hypothesis formulation) until its last stages (refinement, validation and dissemination), and pertain to any potential application domain, such as sciences, design, engineering, or arts (Shneiderman, 2007). Such systems can be classified with regard to the creation process of participants as group or individual creativity support systems (Wang & Nickerson, 2017), or according to the assistance provided as "coaches" that give advice and assistance, "nannies" that monitor and provide an overall framework, or "colleagues" that generate their own ideas and solutions (Gabriel, Monticolo, Camargo, & Bourgault, 2016).

Although there is a considerable number of such systems, in view of the future technological environments, this is a field that has a long way to go in order to better support the complex nature of human creativity. Indicative advancements include to fully support the entire creative process, to provide automatic retrieval and dynamic delivery of stimuli for different levels of relevance to the creation task, and to ensure personalized support for each contributor in a collaborative creation process (Gabriel et al., 2016; Wang & Nickerson, 2017). Additionally, tools will need to reconsider how creation in real world environments can be fostered when the digital will be blended with the physical. The role of big data and AI towards empowering human creativity needs to be further explored, taking into account the potential risks for creativity entailed by over-automation.

7.3. Summary of emerging requirements

Overall, technology has traditionally been used in the contexts of education and creativity, and henceforth this is not a novel field of research. New technologies have the potential to support the emerging learning styles, as they have recently evolved and been influenced by the pervasiveness of technology in the everyday life of the new generations. Personalization and individualization of learning in the future will be paramount, and training that today takes place in physical institutions will be the exception, with learning occurring at the point of need. This transformation will not be limited to lesson plans or even learning styles, but it will also extend to the incorporation of intelligent tutors, AI-driven instruction, targeted mentoring/tutoring, tailored timing and pacing of learning, and collaborative teaming. In any case, the success of technology in education depends to a large extent on HCI issues. How to design learning systems that are appealing, attractive, and engaging to learners of different ages, personalities, educational background, and cultures, is of paramount importance. See Table 7 for a discussion of all the challenges involved, as they have been discussed throughout this section.

In order to truly empower humans towards learning and creativity, the new technological environments need to be truly unobtrusive, avoiding taking the focus from the learning or creativity activities and supporting such activities only when appropriate and at the discretion of the involved participants. In this respect, the way that such technologies will blend in the process and how they will support both digital and physical worlds remain points of future research. In parallel, considerations regarding ethics, privacy and human rights should be principal in the design of future learning and creativity technologies, regulating how big data and AI will come into play.

8. Social organization and democracy

8.1. Definitions and rationale

As humanity moves from smart environments to smart – yet hopefully humane and sociable – cities, and eventually towards smart societies where an abundance of ethical concerns arise, social organization should be supported. With the appropriate technological support, people will be able to better address contemporary fundamental problems such as energy use, pollution, climate change, immigration, and poverty. This role becomes even more crucial in an AI context, in which concerns and fears regarding employment and poverty are already discussed.

HCI research will have a multifaceted pivotal role in the forthcoming technological developments. In that respect, an important strand will be to address major societal and environmental challenges towards societies where the ideals of democracy, equality, prosperity, and stability are pursued and safeguarded. This section explores issues regarding social organization, and in particular sustainability, social justice, and active citizen participation and the role of technology. Furthermore, it discusses how democracy is influenced by the new technological advancements. In all the issues discussed, the challenges that arise for society – to which HCI can actively contribute – are highlighted.

8.2. Main research issues and state of the art

8.2.1. Sustainability

The need for using the power of technology to develop more sustainable patterns of production and consumption is evident through the richness of literature and the breadth of relevant domains, including environmental informatics, computational sustainability, sustainable HCI, green IT and green ICT, as well as ICT for sustainability (Hilty & Aebischer, 2015). Slow HCI is also a relevant research area promoting well-being for individuals, society, and the natural environment (Coventry, 2012). In the face of the new technological era and its associated consumer attitudes, as they have been already shaped through the widespread use of mobile devices, IoT, and big data – and are expected to be further escalated in the future – sustainability research needs to address a number of novel challenges.

The discussion on sustainability is rich, however, an approach that is gaining interest is that of systems thinking. According to this approach, "sustainability is the ability of systems to persist, adapt, transform or transition in the face of constantly changing conditions" (Williams, Kennedy, Philipp, & Whiteman, 2017, *p.* 13). Therefore, in terms of "systems thinking", sustainability needs to be reconsidered in the context of different scales, including a greater diversity of stakeholders and ecologies of

Table 7. Challenges for learning and creativity in technologically advanced and intelligent environments.

Main Issues	Challenges
New generation of learners	• New learning styles of young learners and novel attitudes • Generalizations about the technology skills and learning styles of young learners may lead to exclusion • Support for personalized learning and adaptation to each individual learner
Extended Reality	• Interference with learning and pedagogical goals • Detraction of students' attention to the technology • Learning adaptation to accommodate technology limitations • Skills required by students and teachers to use the technology • Difficulty in creating content • Multi-disciplinary development approach
Mobile learning	• Design of learning activities to accommodate formal and informal contexts, as well as physical and virtual worlds • Lack of quantitative studies regarding the long-term impact of mobile technologies for learning • Learning experiences are mostly classroom-oriented and not yet mobile
Serious games for learning	• Scarcity of real evidence from long-term studies on the educational impact of serious games • Design for fun and fun evaluation in the user experience • Balance between seriousness and fun • Development of design processes, metrics and evaluation tools focusing on the assessment of students' learning progress • Active involvement and collaboration of various stakeholders
Intelligent environments	• Provision of the right material to learners, at the right time and in the right way • Potentially conflicting needs of co-located learners: the decisions of one can be affected by the desires of others • Privacy and ethics concerns, raised by the monitoring capabilities of the environment • Human rights concerns (*e.g.* avoid excessive control by the technological environment, educators or parents) • Use of persuasive technologies in learning environments • Over-abundance of technology without serving tangible educational needs • Risk of making learners dependent on technologies • Improvement of human learning ability making at the same time learning effective and effortless
Pedagogical impact of learning technologies	• Technology should focus on the perspectives and needs of learners themselves and push the boundaries of education • Consideration of learning goals before pursuing specific objectives through technology • Different performance of a technology in varying economic, social, and cultural environments • Adaptable and customizable technology to serve a wide range of user (learner and educator) and context attributes • Extensive involvement of educators in the design and development process
Creativity	• Support for learners not only as individual actors, but also as creative actors that collaborate with the learning environment • Support for the complex nature of human creativity • Automatic retrieval and dynamic delivery of stimuli for different levels of relevance to the creation task • Personalized support for each contributor in a collaborative creation process • Creation in technologically augmented environments, where the digital will be blended with the physical

connected devices (Knowles, Bates, & Håkansson, 2018). Climate rules and ecological limits in terms of natural resources, should also be taken into account towards proofing the future (Knowles et al., 2018). The population explosion, as well as food sustainability constitute points of concern too (Norton et al., 2017). To address this, HCI can contribute throughout the process, by mapping requirements stemming from the analysis to design ideas and solutions. As Coiera (2007) expressed it "we need to put technical back to sociotechnical", through a formal and structured way of describing events and insights at the socio-technical level, and associating them with system behaviors and design specifications, in order to achieve better interventions.

Research should also be carried out towards the design of technologies that will be appropriate for a future with a scarcity of resources, handling crisis response issues and designing for situations when availability on infrastructures may be low (*e.g.* natural disasters), healthcare may be deficient, food supply may be unreliable and governments weak or corrupted (Chen, 2016).

Sustainability also encompasses a variety of other issues related, for example, to population, poverty, peace and security, and social transformation (Silberman et al., 2014). In this context, technology should be used to support local communities and infrastructures, such as through decentralized infrastructures and support for local activities (*e.g.* locally generated energy supplies, or local agriculture) (Knowles et al., 2018). The technological interventions necessary in all the above sustainability issues are not easy or straightforward. However, HCI can contribute with knowledge and expertise to analyze requirements, address design and interaction issues, and assess the actual usage and impact of the designed technologies.

8.2.2. *Social justice*

Technology can advocate for social justice and when possible, reduce inequality and injustice (Knowles et al., 2018). Currently, inequalities mainly pertain to specific social groups (identifiable by gender, class, race, physical ability, *etc.*). In the future, as it will be shaped by technological evolution, other forms of inequalities may become alarming. Such inequalities may be spatial (the rural-urban divide which may be further increased as the new modes of transportation will not be equally available everywhere), informational, and structural (unequal power relationships determining who will eventually impact the future) (Chatterton & Newmarch, 2017). In this context, an acute current and future concern is to design technologies for migrants, who face social difficulties with communication and socialization, as well as with language and literacy (Brown & Grinter, 2016; Fisher, Yefimova, & Yafi, 2016). From this perspective, technology should not only be designed for long-term use, but also in anticipation of transient use when appropriate, assisting specific users to overcome particular challenges they face at a given time without making them dependent for long-term on technology (Brown & Grinter, 2016).

Within a broader social justice perspective, when designing a technology, a principal concern should be who benefits from this technology and if there is a way to design it in a more inclusive way, in order to benefit other social classes more equitably (Ekbia & Nardi, 2016). A social justice orientation can be enacted through appropriate design strategies, such as designing for transformation in a constantly evolving context, recognition of unjust practices and phenomena, reciprocity, enablement of people to fulfill their potential, equitable distribution of resources, and accountability (Dombrowski, Harmon, & Fox, 2016). Eventually, in the long run, future narratives will also require an understanding of how inequalities could be changed, and the pursuit of social and cultural changes along with the imminent technological changes (Chatterton & Newmarch, 2017). Addressing inequalities should also include issues regarding the digital divide (van Dijk, 2012), and how it will evolve in the near future (see also the discussion in Section 5.2.5). In any case, HCI will have an active role in pursuing social change, through seeking to understand the needs of individuals and communities at the risk of exclusion, as well as through the design and development of appropriate solutions. More importantly, HCI can contribute with novel design strategies and framework to enact social justice design in practice.

8.2.3. Active citizen participation

The above highlight a public dimension of design, whereby designers engage with issues that are relevant for the society in which they live (Teli, Bordin, Blanco, Orabona, & De Angeli, 2015). Such a public design approach, dealing with complex and diverse contexts and addressing societal and political issues, cannot be fruitful without the active participation of technology recipients themselves. Engaging citizens in design activities regarding their environment and communities (aka digital citizens) can lead to valuable outcomes such as job creation, social cohesion and inclusion, quality of life enhancement, and innovation capacity (Barricelli, Fischer, Mørch, Piccinno, & Valtolina, 2015). For instance, the approach of digital or city commons proposes the design of shared artifacts (*e.g.* community-managed resources) which can be taken over and self-governed by concerned people, thus nourishing social relations and making technology an object of collaborative production (Balestrini et al., 2017; Teli et al., 2015).

Active citizen participation is closely related to the concept of Citizen Science (CS). CS broadly refers to involving citizens in science and can involve participatory research and participatory monitoring, that may be targeted to a specific research question or be open-ended (Lukyanenko, Parsons, & Wiersma, 2016; Preece, 2016). In brief, CS – a field that has gained increased popularity and attention over the course of the past few decades – is the process in which citizens, including non-scientists, can contribute to the scientific knowledge of a large-scale scientific study. The involvement of citizens in design and science activities raises numerous challenges regarding user participation, methods and results, as well as technology itself. A major concern regarding participation is how to engage citizens in impactful participation, and how to encourage long-term participation and inclusion (Knowles et al., 2018; Preece, 2016). An important aspect in this context is the notion of "open data" as they are collected and provided by different cities and organizations.[4] Open data play also an important role in the concept that being a "smart" city means also to be a 'self-aware' city (Streitz, 2018), where the city "knows" about its states and processes and provides these data in a reciprocal way to the citizens. In turn, citizens are encouraged to provide data to the cities' data pool as part of what is called "civic computing" (Konomi, Shoji, & Ohno, 2013).

To this end, and towards creating cultures of participation, the role of trust, empathy, altruism, and reciprocity (Barricelli et al., 2015), and differences of cultural attitude towards these emotional motivations (Marcus, 2000, 2006) need to be studied. Regarding the methodologies involved, a point that merits attention is the potential risk of information and collaboration overload to which citizens may be exposed (Barricelli et al., 2015), while as far as results are concerned the quality and reliability of the resulting artifacts are of essence (Barricelli et al., 2015; Preece, 2016). Lastly, the role of technology itself needs to be further explored, studying how technology can enable coordination between civic actors (Knowles et al., 2018), as well as what kind of technology and infrastructure is more suitable according to the involved users, tasks, and contexts of use (Preece, 2016).

However, beyond the vision of empowerment and participation and the potential that such approaches hold, it is often the case that participants in such activities are mostly from the upper and middle social classes; populations at the risk of exclusion, such as women or minority populations, exhibit low involvement (Ames et al., 2014). The role of social justice and how it can really be aimed at and achieved through technology is therefore a focal point, especially taking into account the potential crisis and dark future scenarios that fields related to sustainability deal with.

8.2.4. Democracy

Besides the aforementioned potential benefits resulting from the active participation of citizens in technology design, citizens also have the potential to become "agents of democracy with and through technologies and in dialogue with the institutions that can actualize public will" (Vlachokyriakos et al., 2016). Pervasive technologies are believed to encourage and facilitate citizen participation and collaboration with civic authorities (Harding, Knowles, Davies, & Rouncefield, 2015). In this respect, the ease of retrieving information and interacting with others (including policy makers) can help to promote democracy. For example, for e-government to be successful, HCI contribution is important, as systems need to be usable, accessible, and useful to all citizens and even non-citizens. However, currently the perceived value of civic engagement technologies remains low, due to limited success in addressing the needs of all the stakeholders involved (*i.e.*, both citizens and authorities), in order to establish a relationship of trust (Harding et al., 2015).

Democracy is an ideal which technology visions promise to promote and make tangible in everyday life; however, reality often contradicts such declarations and turns them to wishful thinking. For instance, it has been argued that the Internet and social media would increase the availability of perspectives, ideas, and opinions, yet in reality information is eventually "filtered" by algorithms that actually decrease information diversity (Bozdag & van Den Hoven, 2015). Besides "filter bubbles", other technological perils to democracy include fake news, echo chambers (*i.e.*, shared social media bubble with like-minded friends, resulting in restricted access to a diversity of views), and agenda shaping by increased visibility of the most popular stories in media (DiFranzo & Gloria-Garcia, 2017; Flaxman, Goel, & Rao, 2016). What's more, it has been stressed that technological monopolies bring the threat of molding humanity into their desired image of it (Foer, 2017). Such fears become even worse with powerful big data and AI technologies that can lead to an automated society with totalitarian features, where AI would control what we know, what we think and how we act (Helbing et al., 2019). Moreover, the extended use of surveillance cameras in intelligent environments could, under circumstances, pose threats to humans' free will. Standing at crossroads, strategic decisions should be influenced by the principles of AI transparency, social and economic diversity, collective intelligence, and technology decentralization, reducing information distortion and pollution (Helbing et al., 2019). In this new era, HCI is called to play an important role for the design of technologies focusing on human needs and rights, and providing the methods and tools to achieve this.

8.3. Summary of emerging requirements

In sum, the critical times we live in, as well as future dark scenarios, have already directed research towards creating technology to assist humanity in coping with major problems, such as resource scarcity, climate change, poverty and disasters. Social participation, social justice, and democracy are ideals that should not only be desired in this context, but also actively and systematically pursued and achieved. In this respect, the dynamics of new technologies bring challenges (Table 8), but also promises. For instance, it has been claimed that the recent development of blockchain technology could lead to a new era of genuinely participative democracy (Jacobs et al., 2018). Current and future decisions and practices will determine if promises will become guarantees or if challenges will turn to dystopian realities.

9. Discussion and conclusions

This paper has discussed seven main challenges that arise in the current socio-technological landscape, with a view to exploiting the increasingly available interaction intelligence in order to respond to compelling human and societal needs. Although motivated by recent technological advancements and intelligence, the discussion has principally advocated a future technological fabric where intelligence will be employed to better serve the needs of humans and truly empower them. In this context, the HCI community is called upon to undertake an important endeavor and safeguard the design of a future in which intelligence integration does not undermine human self-efficacy and control; instead it becomes a powerful tool (Farooq, Grudin, Shneiderman, Maes, & Ren, 2017).

A central issue in this context is that of the symbiosis of humans with smart ecosystems (Challenge 1), which extends well beyond technical boundaries and requires multi-disciplinary approaches with the aim to also address ethical, societal and philosophical compelling issues. This entails a number of considerations, such as incorporating human values in design methods and choices, revaluing humanistic concerns, and considering social dynamics. A number of important concerns also arise, including designing for meaningful human control, ensuring systems' transparency and accountability, and accounting for intelligent systems' inherent opacity and unpredictability. Ultimately, designing intelligent systems that can work truly in concert with the user is anticipated to be one of the key success factors of intelligent technologies. To this end, intelligence means supporting humans, anticipating their needs, recognizing and responding to human emotions and fostering human safety.

Interaction in forthcoming technological environments (Challenge 2) will radically shift. Information such as users' location, posture, emotions, habits, and intentions will constitute input data. A variety of visible and

Table 8. Challenges of technologies for the support of social organization and democracy.

Main Issues	Challenges
Sustainability	• Adopt a systems thinking approach • Escalated device ecologies and stakeholders involved in the design of technology • Climate change and ecological limits (*e.g.* natural resource limits) • Population explosion and food sustainability • Crisis response • Focus of sustainability undertakings on the social aspect of issues
Social justice	• Digital divide • New forms of inequalities: spatial inequalities, information, and structural • Appropriate design strategies and frameworks for the enactment of social justice • Design of technology not only for long-term use, but also for transient use when appropriate • Pursuit of social and cultural changes along with technological change
Active citizen participation	• Impactful and long-term citizen participation • Information and collaboration overload of the citizens • Quality and reliability of artifacts • Low involvement of minority populations • Creating cultures of participation • Coordination between civic actors
Democracy	• Low civic engagement • Information control by technology monopolies and opinion forming • AI control of what we know, what we thing, and how we act, leading to an automated society with totalitarian features • Impact of increased surveillance on humans' free will

invisible technological artifacts, as well as robotics and autonomous agents will be embedded in the environment. Information will be communicated, from one interaction counterpart to the other, naturally, while the digital will coexist with (and augment) the physical. This evolution paves the way towards evolving existing design and evaluation methodologies, by taking into account the shift from explicit to implicit interaction, the integration of interaction devices into furniture and accessories, the escalation of interaction towards involving ecologies of artifacts, services and data, and addressing larger user populations, the need to reduce information overload, as well as the need to scale up and evolve existing methods in terms of acquiring and framing contexts of use, eliciting and analyzing user requirements, producing designs, and taking advantage of the inherent technological infrastructure towards assessing the user experience.

Ethics, privacy, trust and security (Challenge 3) have always been important concerns in relation to technology, acquiring yet new dimensions in the context of technologically augmented and intelligent environments. Such topics span across all technological domains, with their main questions being common, although different domains may pose supplementary concerns. In general, trust is hard to come by and requires initial trust formation and continuous trust development, requiring not only transparency, but also usability, collaboration and communication, data security and privacy, as well as goal congruence. To this end, intelligent systems need to behave so that they are beneficial to people beyond simply reaching functional goals or addressing technical problems, by serving human rights and the values of their users. A new code of ethics should be pursued in three directions: ethics by design, in design and for design. In this new code, user privacy should be further shielded, especially since the intelligent technological environments feature such an abundance of information and knowledge about the user, as well as automated information analysis and the potential for opinion forming.

Today's technological advances, coupled with advances in medicine, offer the opportunity to provide more effective and less expensive ways of fostering a healthy life by promoting and supporting healthy behaviors, encouraging prevention, offering new forms of therapy and managing chronic illness (Challenge 4). Moreover, in a world where technology is omnipresent, the question arises of how its role towards enhancing well-being and human happiness can be optimized. In fact, technology offers the opportunity to promote not only health, but also psychological well-being through life goals' fulfillment by helping to prevent, reduce and manage stress, depression and psychiatric illness, as well as by fostering purposefulness, self-confidence and positive feelings. To this purpose, concise and useful indicators need to be developed to measure well-being by considering not only individual and community, but also environmental factors.

As HCI has always focused on the human, in the new technology-augmented environments it will lead efforts towards improving the quality of life of various populations, including the disabled and older persons (Challenge 5). Forthcoming technological environments will not be simply the smart home or workplace, but entire smart cities. Taking into account that technology will be a vital component of any daily activity and it will cater for humans' needs, prosperity, and well-being, the stake for universal access is now much higher than in the past. Particular attention needs to be paid to any individual at risk of exclusion, so that the new technologies do not exclude or isolate anyone. In this context, universal access becomes a matter of paramount importance in the forthcoming future, when access to technology will not only mean access to information, but to well-being and eudaimonia.

Technology has traditionally been used in the context of education and creativity. New technologies have the potential to support the emerging learning styles of the neo-millennial generation, as they have recently evolved and have been influenced by the pervasiveness of technology in the everyday life (Challenge 6). However, in order to truly empower humans towards learning and creativity, new technological environments need to be truly unobtrusive, avoid taking the focus away from learning or creative activities, and support such technological activities only when appropriate and at the discretion of the involved participants. In this respect, the way that such technologies will blend in the process and how they will support both digital and physical worlds remain open research issues.

Finally, the critical times we live in, as well as potential future dark scenarios, have already directed research towards creating technology to assist humanity in coping with major societal problems, such as resource scarcity, climate change, poverty and disasters (Challenge 7). Social participation, social justice, and democracy are ideals that should be actively and systematically pursued and achieved in this context. In this respect, the dynamics of new technologies bring challenges, but also promises, in particular concerning sustainability, citizens' involvement and democracy. Current and future decisions and practices will determine if promises will be fulfilled, or if challenges will turn into dystopian realities.

The main research issues for HCI, emerging from the analysis conducted, are summarized in Table 9.

The above research issues are not exhaustive. Instead, they summarize the views and research priorities of an international group of 32 experts, reflecting different scientific perspectives, methodological approaches and application domains. There is a long way to go to adopt a deeply human(e) perspective on intelligent technologies. Tackling these challenges and investigating the emerging research issues require synthetic activities under a broad multidisciplinary scope: international and global research collaboration, enhanced collaboration between academic and research institutions and industry, revaluing the role of humanities and social sciences, novel approaches to HCI academic education and a rethinking of the role and training of HCI professionals and practitioners at a global level.

Table 9. Main research issues stemming from the analysis of the seven Grand Challenges for living and interacting in technology augmented environments.

Human-Technology Symbiosis
- Foster meaningful human control supported by technology transparency, accountability, and understandability
- Design for humane intelligence that brings to the forefront human values
- Develop new methods and techniques for adaptation and personalization to human needs, based on big data, smart environments' infrastructure and AI
- Support and enhancement of human skills
- Emotion detection: capturing and correlating human emotional expressions
- Affective technology exhibiting emotions and empathic behavior, without "nudging" or deceiving humans
- Human safety: 'safety by design' and new testing methodologies

Human-Environment Interactions
- Support for shifts of interaction and attention
- Design for interaction intensive experiences that are not invasive
- Avoid imposing high perceptual and cognitive demands, confusion, or frustration
- Ensure control and accountability of the intelligent environments
- Blend the physical with the digital and make everyday objects intuitively interactive
- Design natural, multimodal and multi-sensorial interactions
- Scale up and evolve existing HCI methods and approaches to address what the new complicated and escalated interactions dictate
- Use 'intelligence-as-a-service' as material for design
- Develop new evaluation methods and tools, taking advantage of the intelligent infrastructure
- Design for public interactions, accommodating a wide variety of users, technologies, styles of engagement, addressing issues related to privacy, transient use, and collaboration
- Design virtual reality environments achieving realistic user experience and supporting social interactions in the VR environment
- Evolve UX evaluation in VR environments towards the assessment of VR attributes beyond subjective assessment

Ethics, Privacy and Security
- Ethics regarding HCI research in public spaces, involving vulnerable user populations, using public online data
- Address concerns regarding over-attachment to technology (*e.g.* Virtual Agents, eHealth technologies)
- Privacy and data ownership in new technological environments featuring IoT, big data, smart artifacts and AI
- Account for threats induced by IoT, big data and AI (*e.g.* advanced profiling, automated decision-making leading to discrimination, persuasion without user awareness)
- Explore the design trade-offs between privacy and smartness
- Foster ethical decision making and responsibility of intelligent agents
- Support AI transparency in a usable manner
- Participate in the establishment of a new code of ethics in the era of robots and AI agents
- Pursue usable cybersecurity
- Raise security awareness in individuals and organizations

Well-being, Health and Eudaimonia
- Account for privacy and confidentiality of sensitive and personal data
- Address issues related to controllability, integration and accuracy of data from
- multiple self-tracking devices
- Account for high error potential from patients untrained in medical data interpretations
- Address ethical concerns stemming from the use of persuasive strategies in the context of health and well-being
- Bridge the high cost induced by the demanding user expectations and the need for multi-disciplinarily in serious games for health
- Evaluate the actual impact of technological interventions in health
- Develop novel design, evaluation and testing methodologies for patient-centric design, also ensuring the accuracy of technologies, eliminating risks for patients'
- well-being and life
- Advance towards fostering human eudaimonia in a more holistic approach

Accessibility and Universal Access
- Reduce the increased cognitive demands that will be imposed by the inherent complexity of forthcoming technological environments and the need for transparency
- Exploit inherent features of technologically augmented environments for universal access
- Address the escalated accessibility needs, pertaining to each and every device and service, the whole environment, as well as the combination of the physical and the virtual
- Understand the evolving human needs and context of use and develop appropriate models
- Advance knowledge of user requirements and of the suitability of solutions for the different combinations of user and context characteristics
- Develop appropriate architectures and tools, ready-to-use accessibility solutions
- Pursue universal accessibility (to information, well-being and eudaimonia)

Learning and Creativity
- Support and promote new learning styles, creative learning and lifelong learning
- Design learning technologies for all learners, avoiding to focus on tech-savvy generations
- Design technologies that are gracefully embedded in the educational process and do not disrupt learners, focusing on the needs of learners and educators
- Design serious games featuring the appropriate balance between seriousness and fun
- Design for tangible educational needs and not be steered by current technological capabilities
- Address privacy concerns regarding the extensive monitoring of students (potentially under-age)
- Address ethical concerns regarding data ownership and management
- Address human rights concerns (*e.g.* potential for excessive control restricting the freedom of the individual)
- Extensively involve educators in the design of learning technologies
- Evaluate the actual long-term impact of learning technologies
- Provide support for personalized creativity and for the amplification of human creative skills
- Provide support for the entire spectrum of creative activities and for the creative process
- Provide support for creativity in smart environments, blending digital and physical artifacts

Social Organization and Democracy
- Adopt a systems thinking approach to sustainability, bringing the technical perspective to sociotechnical analysis and mapping requirements to tangible solutions
- Contribute methods and tools to achieve sustainable design
- Promote appropriate design strategies and frameworks for the enactment of social justice
- Engage citizens in design activities, supporting impactful participation, avoiding information and collaboration overload of the citizens and ensuring the quality and reliability of the designed artifacts
- Design technologies for and with minority populations
- Design for civic engagement technologies taking into account all the stakeholders involved
- Promote the ideals of social participation, social justice and democracy through technology

Notes

1. An indicative list of communities and organizations working on ethics:
   - The IEEE Global Initiative on Ethics of Autonomous and Intelligent Systems: https://standards.ieee.org/industry-connections/ec/autonomous-systems.html
   - OCEANIS Open Community for Ethics in Autonomous and Intelligent Systems: https://ethicsstandards.org/
   - AI Now Institute: https://ainowinstitute.org/
   - Partnership on AI Initiative: https://www.partnershiponai.org/
   - Open Roboethics Institute: www.openroboethics.org/
   - Foundation for Responsible Robotics: https://responsiblerobotics.org/

   AI Global: https://ai-global.org/.
2. https://nypost.com/2018/11/13/i-married-my-16-year-old-hologram-because-she-cant-cheat-or-age/.
3. https://en.wikipedia.org/wiki/Eudaimonia.
4. https://www.europeandataportal.eu.

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List of abbreviations

AAL	Ambient Assisted Living
AI	Artificial Intelligence
AmI	Ambient Intelligence
AR	Augmented Reality
CCTV	Closed Circuit Television
GDPR	General Data Protection Regulation
HCI	Human – Computer Interaction
ICT	Information and Communication Technology
ITS	Intelligent Tutoring System
IoT	Internet of Things
IT	Information Technology
MR	Mixed Reality
OSN	Online Social Network
PMD	Personal Medical Device
UX	User Experience
VR	Virtual Reality

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