

Are Ambient Intelligence and Augmented Reality Two Sides of the Same Coin? Implications for Human-Computer Interaction

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ABSTRACT

We revisit the foundational principles of Ambient Intelligence (AmI) and Augmented Reality (AR) environments to discuss the perspective that AmI and AR feature the same vision of computing, as intuited at their origins, despite their recent development into what may appear as two distinct areas of scientific investigation. We focus on three concepts core to both AmI and AR, on which we capitalize to argue that a significant philosophical overlap exists between their visions: (1) the concept of an environment that undergoes a form of augmentation, (2) the indispensable process of an integration involving the environment, and (3) the emergence of a specific form of media congruent with the characteristics of the environment in which they are created, transmitted, and consumed. We draw implications for the science and practice of Human-Computer Interaction regarding new interactive environments enabled by the technologies of AmI and AR used conjointly.

CCS CONCEPTS

• **Human-centered computing** → **Ambient intelligence; Mixed / augmented reality; Ubiquitous and mobile computing systems and tools; HCI theory, concepts and models.**

KEYWORDS

Ambient intelligence, ubiquitous computing, augmented reality, mixed reality, human-computer interaction, interactive environments, smart environments, theory, visions of computing

ACM Reference Format:

Radu-Daniel Vatavu. 2022. Are Ambient Intelligence and Augmented Reality Two Sides of the Same Coin? Implications for Human-Computer Interaction. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '22 Extended Abstracts)*, April 29-May 5, 2022, New Orleans, LA, USA. ACM, New York, NY, USA, 8 pages. <https://doi.org/10.1145/3491101.3519710>

1 INTRODUCTION

Ambient Intelligence (AmI) is the vision of electronic environments that are sensitive and responsive to the presence of people, enabled

by advances in miniaturization, networks and communications, sensors, and artificial intelligence [1–3]. A common metaphor for the intelligent services of AmI environments is that of light permeating space, *i.e.*, in Brian Epstein’s [24] words from the Digital Living Room Conference, where the concept of AmI was first introduced, “technology anticipates our needs, in which the intelligence is ambient—much like the light in this room, satisfying our need to see without our even being conscious of it, pervades the entire room. And as long as our needs don’t change, the ambient light continues to unmediatedly satisfy the need” (p. 5). According to this perspective, a common application of AmI has been the always-available, helpful “electronic butler,” emerging in various forms from the diversity of sensors and devices integrated in the environment [18], from voice assistants to interactive wall displays.

Augmented Reality (AR) brings another unique perspective on computing, where virtual content is brought closer to the user, in the physical world, sharing the same physical space with the user [7], *i.e.*, “An AR system supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world” [6, p. 34] in order to “make computer interfaces invisible and enhance user interaction with the real world” [13, p. 78] and to “augment objects in the physical world by enhancing them with a wealth of digital information and communication capabilities” [41, p. 13], according to a few of the most influential perspectives on AR. Common technology to implement AR applications is represented by mobile and wearable devices, such as smartphones, tablets, smartglasses, and head-mounted displays.

It would appear that AmI and AR are two distinct areas of scientific research with different visions, paths, and supporting technology, enabling applications of Human-Computer Interaction (HCI) that make users more effective at performing tasks in the physical world. Newcomers to HCI, interested in applying the technologies of AmI and AR for prototyping new interactive computer systems, would have little difficulty in seeing AmI and AR as conceptually distinct due to differences in their supporting technology and typical applications,¹ different scientific communities,² and also attempts to distinguish between the two by reduction to specific

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CHI '22 Extended Abstracts, April 29-May 5, 2022, New Orleans, LA, USA

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ACM ISBN 978-1-4503-9156-6/22/04...\$15.00
<https://doi.org/10.1145/3491101.3519710>

¹Traditional application areas for AmI have been healthcare [4] and ambient assisted living [38,52], while AR has been applied to video games [66], television [71], computer-supported collaborative work [51], and cultural heritage [16]; see Sadri [54] and Dunne *et al.* [22] for comprehensive surveys of AmI and Azuma *et al.* [6,7] and Billinghurst *et al.* [13] for reviews of AR technology and applications.

²Although contributions related to AmI and AR can be found at traditional SIGCHI venues, such as CHI, UIST, and DIS, distinct communities have emerged with their own, specialized dissemination venues, such as ISAmI (<https://www.isami-conference.net>), JAISE (<https://dl.acm.org/journal/jaise>), ISMAR (<https://ismar.net>) and Frontiers in VR/AR (<https://www.frontiersin.org/journals/virtual-reality/sections/augmented-reality>), to name just a few.

Ambient Intelligence

Frequent descriptors:*

adaptive, anticipatory, conscious, context aware, distributed, embedded, emphatic, integrated, intelligent, personalized, responsive, sensitive, socialized, transparent, ubiquitous, unobtrusive



Augmented Reality

Frequent descriptors:**

aligning and combining real and virtual objects, extent of presence metaphor, extent of world knowledge, immersion, interactive in real time, interface and gateway between the real and digital world, 3D registered, reproduction fidelity, specific form of media

*Epstein (1998); Ducatel *et al.* (2001); Aarts & Encarnação (2006); Aarts & de Ruter (2009); Cook *et al.* (2009); Augusto *et al.* (2013); Acampora *et al.* (2013)

**Wellner *et al.* (1993); Milgram & Kishino (1994); Azuma (1997); Azuma *et al.* (2001); Azuma (2006); Azuma (2009); Billinghurst *et al.* (2015)

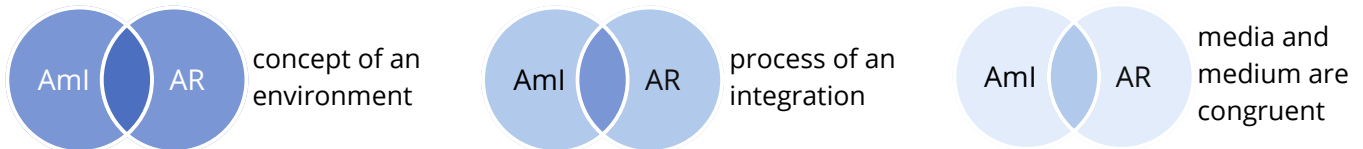


Figure 1: An overview of AmI and AR with frequently used keywords to characterize them (top). Apparently different, the two areas overlap on several aspects—environment, integration, and media (bottom Venn diagrams)—with implications for interactive systems powered by the conjoint use of AmI and AR concepts, design principles, and supporting technology.

application domains. A representative example of the latter comes from PARC [46] that differentiates Ubicomp from AR with respect to their different goals and technology: “Augmented Reality [...] is neither a subset or superset of Ubiquitous Computing. Augmented Reality (AR) is the presentation of electronic information along with a real-world object, projected physically or as seen through an electronic display. Ubiquitous Computing (ubicomp) is the seamless integration of information services as we accomplish goals throughout our work and personal lives. BOTH have to do with the use of information services in conjunction with real-world objects. BUT one is about perceiving ‘reality’, and the other about the usefulness of the ‘computing’ to our goals.”

In this context, a shared inheritance of AmI and AR appears to have been forgotten. In a 1993 special issue of the Communications of the ACM, Wellner *et al.* [74] welcomed applications of “computer-augmented environments,” and noted that “Recent work has been called names such as ubiquitous computing and augmented reality. Although the technologies differ, they are united in a common philosophy: the primacy of the physical world and the construction of appropriate tools that enhance our daily activities” [74, p. 26]. A relevant example is Mackay [41] that connected to ubiquitous computing technology, where objects are detected and tracked by sensors placed throughout a building, to exemplify the AR strategy of augmenting physical objects. This common origin of Ubicomp and AR has often been highlighted during their conceptual and technological development [25,29,41,53,59], but afterwards faded away while the two concepts were embraced by distinct communities. This aspect is unfortunate, because many opportunities for innovation are likely to be missed by ignoring the intersection of these two areas of scientific research and practical developments.

In this paper, we revisit the foundational principles of AR and AmI (or Ubicomp; see Subsection 1.1 for the terminology that we

use in this work) to understand whether they still feature the same philosophy [74] after several decades of theoretical and practical developments. Our main contribution stands with relighting and strengthening the realization that the computing visions described by AmI and AR both overlap and complement each other. To this end, we highlight the concept of a primary environment undergoing integration, in which specific forms of media, congruent with the characteristics of the environment, are created, transmitted, and consumed; see Figure 1. This realization has important consequences for HCI researchers and practitioners that wish to employ the concepts, methods, techniques, and technologies of AmI and AR for building new interactive computer systems that create new user experiences. To this end, we provide three implications for the science and practice of HCI.

1.1 A Note on Terminology

We prefer to use the term “Ambient Intelligence” to describe physical environments that integrate sensing, processing, and communications technology to respond intelligently to people, with the note that there is significant overlap with Ubiquitous Computing [73], Pervasive Computing [55], and Physical Computing [29]. We are not interested in nuances of terminology, which have been discussed elsewhere [1,2,27,36,46]. Rather, we adopt a simple distinction from Kuniavski [36] where AmI, among “the many names of Ubicomp,” describes how “devices appear to integrate algorithmic reasoning (intelligence) into human-built spaces so that it becomes part of the atmosphere (ambiance) of the environment” (p. 4). Also, the word “ambient” from “Ambient Intelligence” conveniently connects to “ambient media” [29,30,60], one of the key concepts on which we capitalize to compare the visions of AmI and AR. We use “Augmented Reality” to refer to the first part of the Reality-Virtuality continuum [44], and see AR as a subset of Mixed Reality (MR).

2 FOUNDATIONS

We start by discussing the core principles and theoretical foundations of AmI and AR by resorting to key papers that have been influential in these areas as well as surveys of AmI and AR.

2.1 Ambient Intelligence

AmI is the vision of electronic environments that are sensitive and responsive to the presence of people [1–3] with the origin in a series of internal workshops organized in 1998 at Philips [24] on the topic of integrated consumer electronics, telecommunications, and computing. Later, Ducatel *et al.* [21] offered a definition of AmI as surrounding intelligent and intuitive interfaces embedded in physical objects, where the environment recognizes and responds to the presence of people in ways that are seamless, unobtrusive, and often invisible. A survey of Dunne *et al.* [22] described AmI as “the application and embedding of artificial intelligence into everyday environments to seamlessly provide assistive and predictive support in a multitude of scenarios via an invisible user interface” (p. 73:1) and also as “an umbrella term for a set of technologies that are embedded into the physical surroundings-seamlessly-to create an invisible user interface augmented with AI” (p. 73:2). In a survey of AmI applied to healthcare, Acampora *et al.* [4] described AmI as “a new paradigm in information technology aimed at empowering people’s capabilities by the means of digital environments that are sensitive, adaptive, and responsive to human needs, habits, gestures, and emotions” (p. 2470).

AmI environments have been characterized with various attributes interpreted as technical requirements [21], quality characteristics [4,23,24], system elements [1], and salient features [2,18]; see Figure 1, left for such frequently used attributes. For example, the original vision of AmI as technology for the digital living room of the future [24] was described in terms of embeddedness (many invisible dedicated devices throughout the physical environment), personalization (devices know who the users are), adaptivity (devices can change how they respond to the user and the environment), and anticipation (devices anticipate and satisfy users’ needs without the need of conscious mediation). Context awareness was later added to the list of key attributes of AmI [1,2], creating the connection with Context-aware Computing to enable AmI environments to be sensitive, responsive, and adaptive [18]. A 2001 ISTAG Report [21] enumerated five technical requirements that an AmI system should meet: (1) very unobtrusive hardware, (2) seamless web-based communications infrastructure, (3) dynamic and massively distributed device networks, (4) natural feeling human interface, and (5) dependability and security. Aarts and de Ruyter [1] distinguished between system intelligence and social intelligence for AmI environments, where the first encompasses the above characteristics and the latter specifies socialized behavior (user interaction concepts apply communication protocols that are compliant with societal conventions), empathic behavior (interaction concepts exhibit their awareness of the inner state of emotions and motives of the user), and conscious behavior (the system has an inner state that exhibits a consistent and transparent behavior in its interaction with people and which is recognized by the user as conscientious), respectively. Other qualities, such as transparency (a quality aligned with the concept of the disappearing computer [73]),

ubiquitous presence (appearing and found everywhere), and intelligence (a consequence of learning for adaptation and reasoning for anticipation) have also been frequently used to describe AmI; see Cook *et al.*’s [18] review of AmI technology and applications.

2.2 Augmented Reality

The origins of AR can be traced back to Sutherland’s [65] 1968 head-mounted 3D display. In a 1997 survey of AR technology, Azuma [7] focused on the combination of real and virtual objects that enhance perception of and interaction with the real world, where “virtual objects display information that the user cannot directly detect with his own senses” (p. 3) and the newly gained information helps users performing tasks in the real world. Since then, AR has received several characterizations in the scientific literature, from a variation of virtual environments [7], the middle ground between completely synthetic and completely real environments [7], a region of the Reality-Virtuality continuum [44], intelligence amplification [7], a specific form of media [8], an illusion of virtual and physical coexisting in the same space [9], an ubiquitous user interface to the real world [58], and the interface and gateway to a 1:1 correspondence between the digital and the real world [9]; see Figure 1, right. A technical definition from Azuma [7], which has stood the test of time [13], specifies that an AR system (1) combines the real and the virtual, (2) is interactive in real time, and (3) is registered in 3D. For general surveys of AR, we refer readers to Azuma *et al.* [6,7] and Billinghurst *et al.* [13], while other surveys have focused on specific applications of AR, such as video games [66], AR for television [71], computer-supported collaborative work [51], cultural heritage [16], and specific aspects of the technology and methods used for scientific investigation in AR [20,31,32].

A distinct concept from AR, Mixed Reality (MR) emerged as a theoretical consequence of the Reality-Virtuality continuum introduced by Milgram *et al.* [44,45]. In this continuum, having the physical and virtual worlds as dichotomous extrema, the primary substratum or world that is augmented is determinant for the reality perceived by the user. For example, if the physical world is augmented with virtual objects, the result is AR. However, if the virtual world is augmented with real objects, the reality that results is Augmented Virtuality (AV). Since MR specifies everything in between the extrema of the Reality-Virtuality continuum, MR represents a superset of AR [43–45]. An interesting distinction from Milgram and Kishino [44] is that between “virtual” and “real” objects, for which they proposed three dimensions along which one can distinguish different nuances of MR displays: Extent of World Knowledge (how much the system knows about the world that is displayed to the user?), Reproduction Fidelity (how realistically can the world be displayed?), and Extent of Presence Metaphor (the extent of the illusion that the user is present in the displayed world). These dimensions have been recently revisited by Skarbez *et al.* [63] from the perspective of the coherence of the information provided by exteroception and interoception senses, who proposed the Immersion and Coherence dimensions. Also, Skarbez *et al.* [63] defined MR as the environment in which “real world and virtual world objects and stimuli are presented together within a single *percept*. That is, when a user simultaneously perceives both real and virtual content, *including across different senses*” (p. 4).

3 UNDERSTANDING THE OVERLAP BETWEEN AMI AND AR

Despite a common origin [74], AmI and AR have evolved as distinct areas of scientific investigation and practical application of interactive computer technology. While AmI has capitalized on integrating computing technology in the physical environment to enable intelligent services that understand context and respond appropriately to users, AR has focused on the integration and alignment between the physical and the virtual towards amplifying user intelligence. In both cases, the concept of an *environment* as a substrate for augmentation as well as the process of *integration* between elements belonging to different domains are key to the theoretical formalization of each area. Also, a distinct type of *media* emerging from the integration that adopts the characteristics of the environment in which media are transmitted can equally be identified for both areas. In the following, we discuss three similarities resulting from the visions of AmI and AR: (1) the *environment* that undergoes a process of augmentation, (2) the *integration* of elements belonging to dichotomous worlds, and (3) the specific form of *media* emerging from the integrated environment.

3.1 The Concept of an Environment that Undergoes Augmentation

Both AmI and AR operate with the notion of an environment that is augmented to expand its capabilities to assist users at performing various tasks. In the former case, the physical environment is augmented with sensing, processing, communications, and display technology, e.g., Ishii *et al.*'s [30] ambientROOM employed a variety of non-traditional displays to deliver information in the form of light, sound, and air flow subtly merging with the architectural space. In the latter, the environment undergoes augmentation with virtual content as per the Reality-Virtuality continuum [44]. For example, Milgram and Colquhoun [43] described applications where users take journeys that traverse real, virtual, and mixed worlds. Based on these observations, we present our first postulation:

Postulation #1: The concept of an environment provides the mandatory substrate for any augmentation to take place and, consequently, it is essential to the ontological existence of both AmI and AR.

Support for this realization can be found in the scientific literature of AmI and AR. For example, Aarts and Encarnação [2] explained the meaning of the words “ambient” and “intelligence” from AmI in relation to the environment undergoing a process of augmentation: “The notion *ambience* in Ambient Intelligence refers to the environment and reflects the need for an embedding of technology in a way that it becomes nonobtrusively integrated into everyday objects. The notion *intelligence* reflects that the digital surroundings exhibit specific forms of social interaction, i.e., the environments should be able to recognize the people that live in it, adapt themselves to them, learn from their behavior, and possibly act upon their behalf” (p. 2). Billingham *et al.* [13] described AR from the perspective of a genuine perception of the reality of the physical environment that is augmented: “In an Augmented Reality interface the blending of Reality and Virtuality is a perceptual task in which the interface designer tries to convince the

human perceptual system that virtual information is as real as the surrounding physical environment” (p. 192). By referring to AR, Wellner *et al.* [74] noted: “Computer-augmented environments merge electronic systems into the physical world instead of attempting to replace them. Our everyday environment is an integral part of these systems; it continues to work as expected, but with new integrated computer functionality” (p. 26). Next, we focus on this aspect of integration.

3.2 The Mandatory Process of an Integration Involving the Environment

A technical requirement for the existence of AmI is for the environment to *integrate* technology, such as sensors, communications, and displays of various kinds. Via integration, the environment gains the capability to run intelligent software that understands context (e.g., Who are the users? Where are the users located? What digital devices are they using? etc.) to deliver personalized, adaptive, and anticipatory services [18,24]. For example, systems implementing proxemic interaction [26] leverage distance, orientation, movement, identity, and location of users, digital devices, and non-digital things from a physical environment to enable interactions matched to users’ expectations of how their device ecologies should interact in relation to each other. Computing across these dimensions of proximity needs data from sensors integrated in the physical environment, e.g., video cameras, motion trackers, tag detection systems, etc.; see the Proximity Toolkit [42] and SAPI-ENS [57] for two examples of toolkits enabling access to such data from heterogeneous sensors.

Integration of computing technology in the physical environment is also a technical requirement for the existence of AR. Via integration, the physical environment is sensed, modeled, and aligned with virtual content by software that understands the context (e.g., What is the location of the user? Where is the user looking at? etc.) to deliver appropriate services in the AR environment. For example, the RoomAlive system [33] transforms any room into an augmented entertainment experience with interactive projection mapping delivered by a system of video projector and depth camera units deployed to that room.

These observations lead us to our second postulation, as follows:

Postulation #2: Integration is a mandatory process for the existence of both AmI and AR, in which the physical environment is augmented with elements not native to that environment.

The process of an integration has been frequently highlighted in the literature of both AmI and AR. For instance, Aarts and Encarnação [2] noted: “The salient novel aspect of Ambient Intelligence is the incorporation of the physical world into the interaction between human being and computing devices. This incorporation can be achieved by a massive embedding of intelligent computing devices” (p. XI). When describing pervasive computing environments, Satyanarayanan [55] also relied on the concept of integration: “The essence of that vision was the creation of environments saturated with computing and communication capability, yet gracefully integrated with human users” (p. 10). In his survey of AR technology, Azuma [8] noted: “AR displays will enable natural interactions with

virtual content that is integrated with the surrounding real world, while the users remain engaged with and aware of the real world” (p. 234). Wellner *et al.* [74] described computer-augmented environments that “merge electronic systems into the physical world instead of attempting to replace them. Our everyday environment is an integral part of these systems; it continues to work as expected, but with new integrated computer functionality” (p. 26).

A note needs to be made about the *nature* of the integration that takes place. In AmI, integration is always at a physical level between non-digital things and sensors/actuators, rendering those things smart, intelligent, sensitive, adaptive, etc. In AR, integration can also take place at a physical level, such as video projectors and sensors employed for spatial AR [14], but more often between dichotomous physical and virtual worlds that provide the elements for the integration as per the Reality-Virtuality continuum [45]. An interesting aspect is that the notion of distinct worlds has also been used to describe integration in pervasive computing environments: “By embedding computing infrastructure in building infrastructure, a smart space brings together two worlds that have been disjoint until now. The fusion of these worlds enables sensing and control of one world by the other” [55, p. 237]. What is important is that the integration has similar effects in both AmI and AR. For instance, in their discussion of computer-augmented environments, Wellner *et al.* [74] noted: “We can make the environment sensitive with infra-red, optical sound, video, heat, motion and light detectors, and we can make the environment react to people’s needs by updating displays, activating motors, storing data, driving actuators, controls and valves” (p. 26). This description is identical to the vision of AmI (see Section 2.1) down to the level of individual key words, *e.g.*, environments that are *sensitive* and *react* to people’s needs.

3.3 The Emergence of Media that Reflects the Characteristics of the Environment

A new form of media has emerged in augmented environments, for which the distinguishing trait is manifestation that adopts the characteristics of the environment in which media are created, transmitted, and consumed, *e.g.*, “Instead of various information sources competing against each other for a relatively small amount of real estate on the screen, information is moved off the screen into the physical environment, manifesting itself as subtle changes in form, movement, sound, color, smell, temperature, or light” [75]. In AmI, the new media have been referred to as “ambient media” [29,30,49,50,60], while “ambient displays” [75] became the means for the delivery of information in the physical environment in ways that do not monopolize user attention [29,60]. Ambient media enable communication of information in ubiquitous and pervasive environments within the natural living environment, are intelligent, and react pro-actively to the consumer [39]. These characteristics emerge from the media integrating the environment, *e.g.*, “Lighting, sound, vision, domestic appliance, and personal health care products all cooperate seamlessly with one another to improve the total user experience through the support of natural and intuitive user interfaces” [2, p. 1]. For example, in Ishii *et al.*’s [30] ambientROOM, ambient displays employ light, sound, and air flow to deliver information at the periphery of awareness. Ambient media are also one possible implementation of tangible bits [30].

Although some foundational works in AR/MR [7,44] have focused on visual displays, AR media are not exclusively visual; in fact, Milgram and Kishino [44] acknowledged many display modalities. While visual AR has been predominant, AR systems implementing other forms of media, such as auditory [10,11,28,35], haptic [12,17,67,70], but also imaginary, *i.e.*, content existing only in the user’s mind [10,56], have been described in the scientific literature. Also, AR has been seen as an opportunity to enrich conventional forms of media [62], where it was framed as a new medium with unique characteristics for remediating established media [40], *i.e.*, “The importance and uniqueness of personal AR as a medium is the result of three features that combine to distinguish it from earlier media: blending the virtual and physical worlds, continuous and implicit user control of the point of view, and interactivity. While no one of these features is unique (except, to some extent, the blending of the virtual and physical worlds), the combination is” [40, p. 198]. In a more recent article, Azuma [9] discussed ubiquitous consumer AR systems, for the realization of which AR was envisioned as a new form of media to tell stories and generate new experiences exploiting meaningful and compelling combinations of the physical and virtual. To this end, *AR as media* results from reinforcing, reskinning, and remembering strategies that lead to meaningful connections with the physical environment. In Azuma’s [9] words, “My core hypothesis is that the key to establishing AR as a new form of media is to make the combination of the real and virtual crucial, where virtual content is connected to reality in compelling and meaningful ways, and the experience cannot be derived solely from the real content or solely from the virtual content” (p. 235).

Based on these considerations, our third postulation is:

Postulation #3: The integration process that augments the physical environment leads, for both AmI and AR, to the emergence of a specific form of media that meaningfully reflect the characteristics of the environment in which media are created, transmitted, and consumed.

4 IMPLICATIONS FOR HCI

We propose in this section three implications of our postulations for the science and practice of HCI powered by AmI and AR concepts and supporting technology.

4.1 Using AmI for Innovations in AR Systems and Vice Versa

One immediate implication of AmI and AR being complementary in their visions is that concepts, principles, methods, and technology from one area can be transferred to and used in the other. For example, AR systems can be described in terms of AmI concepts and vice versa. Relevant examples from SIGCHI conferences are IllumiRoom [34] and Around-TV [68], two TV-based systems for home entertainment that were described by their authors from the perspective of spatial AR, whereas the concept of “ambient light” originated in the context of Philips’ vision of AmI [48] and its application to large surfaces [47] was introduced in the context of peripheral displays. Also, systems such as “Smart Pockets” [69] and “I bet you look good on the wall” [72], positioned by their

authors in the context of AmI, could equally be characterized from the perspective of AR, since smart pockets store virtual content in the user's physical pockets and Vermeulen *et al.* employed video projections to show users how an AmI system employs sensors and devices to trigger actions in the physical environment.

Besides characterizing interactive systems from different perspectives, AmI concepts and technology can be used to drive innovations in AR and vice versa. For example, the various quality attributes of AmI environments could be applied to make AR applications adaptive to and anticipatory of users' needs [24] as well as more compliant with societal conventions towards social intelligence [1] mediated by AR; see Subsection 2.1 for other quality attributes. Also, AR/MR concepts and technology could be used to drive further innovations in interactive ambient systems. For example, Milgram and Kishino's [44] Reproduction Fidelity axis characterizes how realistically the mixed world is displayed in MR, whereas in AmI, Reproduction Fidelity could be used to specify the degree in which ambient media are congruent, in terms of manifestation, morphing, and intelligence [39], with the physical environment in which they are transmitted. Furthermore, addressing challenges of AmI and AR, *e.g.*, precise tracking across large environments to support pixel-accurate registration in AR [8], mechanisms to deal appropriately with the aspect of human control *vs.* automation in AmI systems [23,64], and enabling interactive experiences for hundreds and thousands of users in public places [37], by using concepts, design principles, and supporting technology developed in the other area of scientific investigation may be interesting to explore in future work.

4.2 Conjoint Application of AmI and AR Concepts and Technology

Beyond unidirectional infusion of knowledge and technology from AmI to AR and vice versa, their conjoint use may lead to further innovations in interactive computer systems. This implication refers to system designs that share characteristics of both AmI and AR that, in conjunction, create more added value to users than the sum of their parts. For example, both AmI and AR focus on assisting users in their tasks in the physical world, but do so from two different perspectives. While AR strives for the intelligence amplification of the user [7], AmI research has oriented on making the environment algorithmically intelligent [1]. Combined, amplified intelligence of both the user and the environment can lead to higher task effectiveness, more efficient interactions, and better user experience. One specific implementation of the conjoint use of AmI and AR technology is discussed next. Also, large-scale projects, such as moving towards ubiquitous consumer AR systems as envisioned by Azuma [9], will need conjoint development of AmI and AR.

4.3 Cross-Device Interactions Across Wearables and Ambient Devices

Today's predominant technology for AR applications is represented by smartphones, smartglasses, and head-mounted displays. Although wearables have been considered for AmI as well, they have mostly been used in healthcare applications, *e.g.*, body-worn sensors to measure EEG, ECG, blood pressure, etc. [4]. A 2009 special

issue [19] of the Journal of Ambient Intelligence and Smart Environments called for more research at the intersection of wearable computing and AmI: "To date, research in wearable computing and research in smart environments has been pursued independently. However, these disciplines have much to offer each other. For example, fusing data from worn sensors and from passive environmental sensors can facilitate the creation of more comprehensive and more accurate models of resident behavior and well being. In addition, information collected in the environment can be used to predict resident physiological response (validated by wearable sensors) and information collected from wearable sensors can be used to initiate appropriate responses and changes in the environment" (p. 85). Unfortunately, the response from the scientific community has been scarce. We take this opportunity to strengthen the recommendation for innovations in the new context of cross-device interaction [15], where some devices are worn and others are integrated in the environment. Such interactions approach the "scale" dimension from Brudy *et al.*'s [15] taxonomy of cross-device interactions in relation to the progression of Weiser's [73] tab/pad/board computing, but with a twist that reflects intelligence amplification [7] with AR and system intelligence in the environment [1] with AmI. An example is AmI services that provide feedback in the form of visual AR rendered in smartglasses, but also auditory AR with smart earbuds (computer-generated signals combined with natural sounds from the environment), and haptic AR with finger-augmentation devices (synthetic haptic information superimposed on haptic sensations produced by actual physical manipulation), respectively.

5 LIMITATION

We identified and examined in this work, using the lenses of theoretical and practical developments in AmI and AR, three key aspects that strengthen and expand a realization from the origins of the two areas that they are connected [29,41,53,74,74] by a common philosophy and vision of computing. By following the historical development of AmI and AR, we uncovered several similarities, which we formalized with a set of three postulations. However, a limitation of our method is represented by having focused on a selected set of influential papers from AmI and AR instead of adopting a more structured approach, such as a systematic literature review [61]. The latter will likely reveal a richer set of scientific literature and, possibly, lead to an extended set of postulations to characterize the overlap between the philosophy and visions of AmI and AR. Also, interesting future work is to use our foundational postulations to understand the application overlap between AmI and AR, such as their common goal to provide assistance to users [5,7] or the spatial user interfaces they expose [9,64]. For example, a practical investigation may examine the goal of both AmI and AR systems to provide intelligent assistance. In this context, AmI is about "intelligent software that supports people in their daily lives by assisting them in a sensible way" [5, p. 4], while one of the motivations that drives advances in AR, according to Azuma [7], is that AR is an instance of intelligence amplification, *i.e.*, "using the computer as a tool to make a task easier for a human to perform" (p. 3). Such applied aspects of the overlap between AmI and AR can be exploited by HCI practitioners for new interactive computer systems supported by the conjoint use of AmI and AR technology.

6 CONCLUSION

We presented three postulations about the overlap between the visions of computing of AmI and AR. Our postulations centered on the concept of an environment that undergoes a form of augmentation, the process of integration involving the environment, and the emergence of a specific form of media congruent with the characteristics of the environment. We capitalized on these postulations to propose implications for the science and practice of HCI in the form of infusion of concepts, knowledge, and technology from AmI to AR and vice versa and integration of wearable and ambient devices towards new interactive experiences. We hope that our work will benefit HCI researchers and practitioners, and especially newcomers to the field, by providing them with a useful perspective on AmI and AR towards attaining innovations in interactive computer systems powered by the concepts, design principles, and technologies of AmI and AR used conjointly.

ACKNOWLEDGMENTS

This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI-UEFISCDI, project number PN-III-P4-ID-PCE-2020-0434 (PCE29/2021), within PNCDI III. Figure 1 was created with Canva (<https://www.canva.com>) under the Free Content license.

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