A Review of Universal Design in Ambient Intelligence Environments

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***Abstract*—This work summarizes the state of research in universal design in ambient intelligence environments. We provide a detailed background, specify relevant research areas, and review research in these areas. We discuss the findings and put them into perspective with regard to universal design and accessibility in smart environments, and point out research shortcomings concerning ambient intelligence and hybrid interactions. Our findings show that the majority of related work needs stronger emphasis on aspects related to universal design in general; universal design in ambient intelligence; universal design in multimodal interactions; and universal design in security, privacy, and other ethical aspects of smart environments.**

***Keywords*—Universal design; ambient intelligence; multimodal interaction**

I. INTRODUCTION

The United Nations Convention on the Rights of Persons with Disabilities (CRPD) [1] aims to ensure that people with disabilities can enjoy the full range of human rights: civil, political, economic, social, and cultural. Besides the requirements for accessible ICT (Article 2), the Convention refers to universal design (UD) as a means to achieve this goal (Article 4). UD is the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design [2].

Universally designed smart environments have the potential to improve the mental and social well-being of individuals as well as their economy. People with disabilities will have increased independence with a reduced need for aid, other support services, and personal assistants. Smart environments in the workplace mean that a person with disabilities can get work experience early on. This has a direct positive effect for the person and increases the probability of being in the workforce and contributing to society in the future [3].

Stevenson and McQuivey [4] find that 57% of working-age people with mild to severe difficulties or impairments are likely or very likely to benefit from accessible technologies when they use computers. The increased social, cultural, and economic participation of this group is likely to improve their health, which in turn influences their human and economic development positively [5]. Looking at the economic side, the participation of a larger part of the population in the workforce – including people with disabilities – is the key to fostering economic growth: a larger workforce should lead to increased tax incomes and reduced welfare and health expenses. Creating structures and systems to accommodate people with disabilities facilitates the retention and return to work of other workers as well [5].

Yet the focus for smart environments or ambient intelligence (AmI) has mainly been on technology and its capabilities. User-centric design and accessibility are often neither part of the design nor the evaluation process [6]. A vital part of AmI environments implements interactions between users and the environment. To make these interactions accessible and usable for *diverse people* (all people, including people with different types of disabilities) the interfaces must be flexible and offer interaction through different types of modalities [7].

Although multimodal interactions constitute an important concept in universally designed AmI, many AmI solutions lack the aspect of multimodality. It seems we are long way from the *disappearing computer* scenario proposed by Weiser [8]. In this scenario, devices are concealed into everyday objects and everyday interaction modalities, and people spontaneously interact with digital objects as they do with physical ones.

We refer to a combined physical and digital environment as a *hybrid environment*. A universally designed hybrid environment enhances the surroundings with ambient intelligence and digital interfaces so humans can interact according to their abilities and preferences. In this context, a *hybrid interaction* may comprise of both input and output in various modalities and interaction types.

The remainder of the paper is organized as follows: After a summary of the current knowledge state within ambient intelligence and multimodal interactions (Sections II and III) we discuss the challenges of universal design in ambient intelligence and multimodal interactions (Section IV). Finally, we highlight research directions (Section V).

II. AMBIENT INTELLIGENCE

Ducatel et al. [9] define *Ambient Intelligence* (AmI) as a smart environment that supports its inhabitants. The vision for AmI is an environment that is unobtrusive, interconnected, adaptive, dynamic, embedded, and intelligent. Instead of communicating through a keyboard, mouse, and screen, people use implicit interaction with the objects in the environment [10], such as light sources, furniture, or household devices. The devices themselves can communicate with each other through the Internet of Things (IoT) to facilitate collaborative assistance of the environment. Other visions for AmI include that AmI environments can anticipate and predict the people's needs and behavior and provide services or interactions in people's preferred way [11].

AmI has become a complex, multidisciplinary research field and consists of several domains. There are multiple definitions of how AmI can support its inhabitants, but intelligent reasoning, multimodal interfaces, sensors and ubiquitous computing are elements that are usually required for an AmI. The development of AmI's requires specialists from fields like information and communication technology (ICT), psychology, social sciences, engineering, design, security, privacy, and humanities.

Kodratoff and Michalski [12] presents intelligent reasoning as a broad field built on well established theories and methods with machine learning at its core. Mikolov et al. [13] point out that building an intelligent reasoning system must incorporate many parts like models of human behavior, predictions about human actions, user preferences, large amounts of sensor data, and machine learning.

To personalize the environment for a specific person or group of people, a profile is usually built, based on the person's abilities and needs, preferences, context, and history. Large variations in what to store in a profile and how to apply the profile in a given context have been shown by van Otterlo [14]. Koller and Friedman [15] suggest using probabilistic models like Bayesian or Markov networks. These models can predict how likely someone wants to turn on the light, or how likely someone wants to use voice modality instead of textual modality.

Instead of modelling the probabilistic distribution of the data, a common approach is to look at the similarities between the examples using *kernel methods*. Bishop [16] defines a kernel as a collections of algorithms that look at the differences (more formally: distances) between examples in complex data structures. Possible methods suggested by Bishop include support vector machine (SVM) and principal components analysis (PCA).

In the field of human behavior and prediction, much work has been done on modelling human behavior with statistical models within machine learning algorithms [17]. However, due to the *curse of dimensionality* [18] that occurs when analysing high-dimensional spaces, the statistical models of people and their behavior are often too simplistic. Instead of only using statistical models, studies by Rosenfeld et al. [19] and An [20] have combined psychological models with machine learning and achieved good results in more complex domains. Another method used by Panagiotou et al. [21] is to apply machine learning algorithms to sensory data in combination with personal data. A more recent approach for personalization is to build a model for each user from a large dataset. Ghahramani [22] call this the *personalization of models*. Suitable methods for solving these problems include hierarchical Dirichlet processes [23] and Bayesian multitask learning [24].

For an intelligent system to learn and adjust to users, it needs information from sensors, actuators, and monitoring tools. Liu et al. [25] have connected sensor output to high-level intelligence, and Sun et al. [26] have worked on predicting human routines from sensor data. Deep learning and convolutional recurrent neural networks have lately gained much attention in voice and image recognition, but have also given results in activity recognition as shown by Ordóñez and Roggen [27]. Wiering and van Otterlo [28] have used reinforcement learning and feedback loops in a learning system. A vital part of reinforcement learning is the reward function that motivates model adjustment. Barto [29] has incorporated human motivation into these models.

There are several AmI frameworks. Karakostas et al. [30] created a sensor-based framework for supporting clinicians in dementia assessment with several wearable sensors used on the patients. Blackman et al. [31] identified 59 technologies that have been developed for ambient assisted living for the elderly. They also indicate that more research should be done on middleware and integration.

Home environment is probably the most dominant area of application for AmI. Often described as smart or intelligent homes, the integration and utilization of multiple sensors are the center of attention. The goal is to improve quality of life by performing everyday tasks automatically and improve safety by preventing and detecting accidents. For instance, an oven can be equipped with a database of recipes with oven temperature, timing, and method of heating, as demonstrated in the GENIO Project [32].

Ambient assisted living for elderly is another application area in AmI. The goal is to increase the quality of life by providing health care in domestic homes. Kientz et al. [33] show how AmI can monitoring medication use and alert caretakers in case of a person's fall. Other AmI application areas include shops, museums and driving [11]. Lately, also the working environment has seen some progress, with the goal to get more people back to work and to accommodate people at work. The SMARTDISABLE Project aims at including people with disabilities in the workplace by means of ICT equipment with voice control [34]. Another example is a fatigue-sensitive chair aimed at workplaces to alert the user to rest or take a break [35].

Despite many promising applications, only a few evaluations show how AmI solutions works in practice. Gövercin et al. [36] conducted a study with 35 households as part of the SmartSenior@home project, but there are few other evaluations at this scale. There are also few studies that involve real users in the evaluation phase. Often, as shown by Wilson et al. [37], the results show a mismatch between expectations from the users and the developers and designers.

III. MULTIMODAL INTERACTIONS

Humans interact with the world in a multimodal way by using multiple perceptual modalities, both in parallel and sequentially. Turk [38] introduces the concept of *multimodal human-computer interaction* (HCI) as the attempt to provide similar capabilities to computers, and multimodal interfaces are intended to deliver more natural and efficient interaction.

Jaimes and Sebe [39] define a multimodal HCI system as one that responds to input in more than one modality, where modality is understood as communication according to human senses. We would extend the definition of *multimodal interfaces* to include input and output in more than one modality.

There is extensive research on interactions with modalities like visual, auditory, cognitive, touch, gesture, reach, and tactile. Covering all of them is beyond the scope of this paper, but some concepts that have shown good results across different modalities are mentioned here: Ullmer and Ishii [40] define a *tangible user interface* as an interface that couples physical representations with digital representations in a way that leads to interactive systems mediated by computers, and not identifiable as computers. The various meanings of tangible interactions in different science fields are summarized by Hornecker and Buur [41], and common characteristics are tangibility and materiality, physical embodiment of data, embodied interaction, and integration in real space. Recent research on tangible user interfaces includes work on haptics to improve the use of touch screens by Zimmermann et al. [42], and work by Bianchi and Oakley [43] on the use of *magnetic appcessories*, i.e., robust physical interfaces with magnets in interaction with a mobile phone and its built-in magnetometer.

Ferati et al. [44] studied the design of *audemes* (short non-speech sound symbols composed of music and sound-effects) with the goal of highest possible meaning recognition. Audemes can be used as a complement to visual output and to leverage more of the auditory capacities of people with vision impairments. The use of auditory modalities is useful in many case, for instance in eyes-free activities like driving or running. Rohani Ghahari et al. [45] study how one can browse the web on mobile devices with aural flows.

Takeuchi [46] has done work on digitizing architectural spaces, but there are no studies that try to bring the different architectural concepts together to facilitate multimodal interactions. In addition, Takeuchi [46] has proposed habitable user interfaces (HUIs) intended to fulfill the disappearing computer vision by digitalizing the environment. Here, the environment can be as easily transformed as changing the desktop wallpaper background on a modern computer. However, more studies that try to integrate all the different concepts into a complete environment are needed.

In a universally designed AmI environment, multimodal interactions are critical for adaptation purposes. Oviatt [47] and Obrenovic et al. [48] found that interfaces must handle multimodal input and output depending on a person's personal abilities, preferences, and the environmental conditions. The use of multimodal interfaces is one step towards universally designed interaction, but the interaction still must be usable and accessible. For example, a person must understand that a modality (e.g., auditory interaction) is available and know how to use it; the availability of a modality is not enough.

Fuglerud [7] found that introducing several modalities into an interface may make it more complex and, thus, less usable. Much work has been done on multimodal interaction and human-computer interaction, but Turk [38] found that only a minority of these studies focus on UD. Moustakas et al. [49] found that the translation from one modality to the other, an essential part of universally designed multimodal interfaces, is often limited to vision and voice modalities. Alce et al. [50] noted that more studies including diverse people and a larger number of participants is needed.

Homola et al. [51] found that when several humans are in one AmI environment, several types of conflicts can occur, from modality conflicts to goal and action conflicts. Resendes et al. [52] list the extensive research on resolving such conflicts, but Carreira et al. [53] point out that little work has been done with multimodal output conflicts. Also, usability and UD have not been focused on. For effectively working AmI environments, these challenges need to be solved.

IV. DISCUSSION

The idea of UD in AmI is to increase the degree of inclusion and life quality for users. As illustrated in Figure 1, the core entities are *diverse people & UD* (in the middle), *hybrid interactions*, *ambient intelligence*, and *things & environment*. These entities interact with each other, and UD is the key component that is infused in all the components.

Hybrid interactions, i.e., interactions between a user and digital and physical things in the environment must be adjusted for each user, based on preferences and abilities (profiles). The AmI will try to predict the best combination of interaction types and modalities for a given user or group of users. For instance, an older person with impaired hearing might prefer to speak actions out loud, but receive information visually in large type. This combination of interactions, however, might not be suitable for someone with vision impairment who may prefer to receive information as audio or tactile feedback depending on the context.

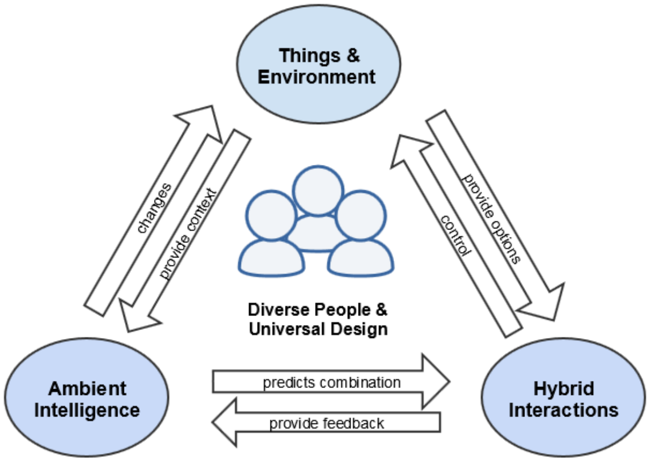

Figure 1. The core elements of universal design in ambient intelligence, and how they are interconnected.

The AmI must learn from previous interactions and associated contexts to improve and validate further predictions. Some things, like a smart rug, might not be able to use audio for interaction, while a talking door could support both visual and auditory interaction, but may not support tactile interaction. To our knowledge, research in AmI has not yet considered UD combined with human behavior and interaction prediction.

As illustrated in Figure 1, UD must be included in all parts of an AmI environment if the vision of AmI is to be fulfilled. As Wilson et al. [37] points out, most of the current AmI research does not have a clear understanding of who the users are and what their needs are, and this must get a stronger focus in the research fulfill the AmI vision.

O Shea et al. [54] note that the common approach for measuring UD is the use of checklists and expert evaluations as well as lab experiments, which are less feasible for practitioners. There are significant challenges in studying the impact of UD in the field, e.g., in buildings. Some of the difficulties include controlling for factors that may introduce confounding influences, e.g., the age of a building, occupancy type, activities occurring in the building, and its size. Sometimes, these issues have been resolved by conducting controlled experiments, or by comparing specific features in buildings, rather than evaluating the overall effect in the building.

The *participants activity index* documented by Danford et al. [55] is an example of a quantitative evaluation method. By means of crowdsourcing, Holone [56] found that users can play a central role in providing the accessibility information by using mobile apps. Moreover, Varela et al. [57] are considering autonomous evaluation, but current research appears to prefer conventional user interfaces rather than interactions. There is a need for research on methods and effective data gathering techniques for evaluating UD in AmI.

A. UD in ambient intelligence

Concerning the design of smart environments, Queirós et al. [6] posits that the limits of technology have been studied rather than the actual people's needs. Tavares et al. [58] is working on ontologies for accessibility, and Catenazzi et al. [59] proposed guidelines for inclusive intelligent environments. More studies that focus on human-centered design and on meeting user needs are called for in the AmI literature [37], [6], [60]. There is also a lack of evaluations including people with disabilities and evaluations in real-life environments.

Corno et al. [61] has proposed a set of design guidelines for user confidence in AmI environments. But there is little work on the cognitive and social aspects in the design of AmI environments nor how cognitive and social aspects can be combined with technology requirements.

Olaru et al. [62] list many AmI system architectures, but not many consider accessibility or UD as part of the system architecture. One platform that has a large community is the Global Public Inclusive Infrastructure (GPII) for making digital technologies more accessible by providing adaptive user interfaces in a cloud based infrastructure [63]. Other frameworks involving UD in AmI environments should be proposed and evaluated.

Currently, there is a lack of research regarding multiple cultures. Kaiying et al. [64] notes that most studies have been conducted in Western countries with a differing view on AmI as compared to non-Western countries. Hence, all cultures should be represented throughout the design, development, and evaluation phase of universally designed solutions.

B. UD in multimodal interactions

The UD aspect of multimodal interactions is deficient in the research, and Turunen et al. [60] requests studies that are more human oriented. This includes finding the best combination of multimodal interaction types and modalities for universally designed AmI environments [65]. Both the accessibility and the feasibility of possible interactions must be evaluated with broadly diversified users and cultures to evaluate what works best in practice.

While there are studies for multimodal output conflict resolution, the focus has not been on usability or UD [53]. If multiple interactions in different modalities are to be realized in an AmI environment, then more user studies must be done to evaluate conflict resolutions.

C. UD in security, privacy, and ethical aspects of AmI

Venkatesh et al. [66] details security-related work in AmI environments, and He and Zeadally [67] document how to provide secure system authentication. To preserve privacy within AmI, Gope and Hwang [68] propose architectures for ensuring that sensory output is untraceable. Sicari et al. [69] list projects that address general privacy and security aspects in the IoT.

Even though Nurse et al. [70] stress that usability is important for security, Realpe et al. [71] point out that UD has not been a focus area. Fritsch et al. [72] show that UD introduces additional challenges in relation to personalization, privacy, and the design of the security mechanisms themselves. Privacy is paramount when users interact with ambient environments. There is a need for anonymity and pseudo-anonymity, exemplified by systems which give people the choice to opt-in for the disclosure of their profile and data to the services. We did not find research that considers universally designed security and privacy solutions in the context of AmI and interactions.

Further, a review by Novitzky et al. [73] finds that ethical questions have not been a research focus of AmI and ambient assisted living; more research is clearly needed. Bibri [74] has suggested to implement safeguards for protecting privacy, but there is a lack of research not on how to incorporate ethical concerns during the development process in general and on ethics in combination with AmI and hybrid interactions. There is a need for research on how AmI solutions may affect autonomy, integrity, dignity, human contact, and human relations.

V. CONCLUSION AND FUTURE WORK

We have given an overview and highlighted some important issues and new areas for research in the field of universal design in AmI environments. Clearly, much research work remains. This view is also supported by several studies that point out the failure of meeting user needs. Even though there are guidelines for designing inclusive AmI solutions, there are very few user studies of AmI in general. There are even fewer studies that evaluate the AmI solutions for users with disabilities. Therefore, future work should develop AmI solutions that consider the full spectrum of user abilities and involves a number of diverse user groups throughout the entire development process, including users from different cultures.

It would be interesting to see more automated evaluation methods for measuring the effect of UD and usability in AmI environments. Methods like crowdsourcing and autonomous data gathering are possible ways to measure UD, and we believe that a higher degree of automation could in turn stimulate more user studies.

From our literature search, no AmI research has considered UD combined with human behavior and interaction prediction. Further, there seems to be a need for research on ethical and social aspects of AmI solutions.

Finally, security and privacy issues abound in AmI environments. Particularly, security and privacy mechanisms must be reliable and usable for diverse people. Future research should contribute to the development of novel, universally designed security mechanisms that offer comparable protection for all users as current regular systems.

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