Assistive Technology in the Synchrony between Ambient Intelligence and Mixed Reality for People with Motor Disabilities

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Abstract We conduct a meta-analysis of scientific contributions in assistive technology, systems, and applications designed for people with motor disabilities and/or limited mobility at the intersection of Ambient Intelligence and Mixed Reality environments. Our findings show that most of the scientific contributions have focused on navigation, rehabilitation, and video games; systems outnumber user studies; and the most frequently implemented attributes of Ambient Intelligence environments have been sensitivity, responsiveness, and adaptation. Our survey also shows that work at the intersection of Ambient Intelligence and Mixed Reality for people with motor disabilities has been scarce despite the opportunities enabled by these two research areas in conjunction to increase access to digital information and services.

1 Introduction

People with motor impairments and/or limited mobility experience challenges with interactive computing devices, applications, systems, and technology that were not designed with accessibility in mind. Prior work has documented accessibility challenges for the desktop [13,29], mobile [19,41,44], and wearable [5,22,35] computing paradigms and for various contexts of use [25, 39, 40]. Beyond these paradigms, interactions in mixed environments that combine the physical and the virtual, i.e.,

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Augmented and Mixed Reality (AR/MR) [24, 28, 38] and, respectively, in smart environments featuring responsiveness, adaptation, and intelligence attributes [6, 7] bring new challenges, but also opportunities to increase access to computing technology and digital information and services [11]. Designing applications and systems that adapt to users' needs, are anticipatory of those needs, and respond intelligently to the presence, movement, and actions of users in a given environment [6] is important to increase access to public services. At the same time, designing systems that superimpose virtual content on top of the physical world [24, 38] to provide more information to users and render users more effective at interacting with the physical world completes the desiderata for universal access to Ambient Intelligence (AmI) environments [11]. To understand the state of the art in this area of research, we report findings from a literature review of scientific contributions proposed in the synergy between AmI and MR environments for users with motor disabilities.

2 Scope and Method

We target three research objectives with our literature review: (1) understand scientific contributions addressing people with motor impairments in smart environments intertwining the physical and the virtual, (2) characterize those contributions from the perspective of AmI characteristics [6] and defining attributes of MR [38], and (3) identify opportunities for future work on assistive technology in the synergy between AmI and MR. To this end, we use the tools of meta-analysis [21, 34].

2.1 Study Design

We identified relevant papers found at the intersection of AmI and MR scientific research by running the following query in the ACM DL[1] and IEEE Xplore[2] databases:

```
"query": {
   Abstract:(((motor AND (impair* OR disab*)) OR wheelchair*) AND
   (environment* OR ambient*) AND
    (augmented OR mixed OR glass* OR HMD*))
 }
"filter": {Publication Date: (* TO 12/31/2020), NOT VirtualContent: true}
```

This query employs specific keywords and wildcards to identify the target user category, the ambient or environment, and AR/MR technology, including common devices for AR/MR. We ran the query on the paper abstracts as a compromise between searching through the titles only (too few results) and the full text (too many irrelevant results), and found 77 references; of these, 10 were duplicates (i.e., papers that were indexed in both databases). We read the abstracts of the identified papers to determine their relevance to our scope and removed 7 papers not addressing people

[1] https://dl.acm.org

[2] https://ieeexplore.ieee.org/Xplore. The query ran in IEEE Xplore had the same keywords, but a different form. Both queries were ran on February 26, 2021.

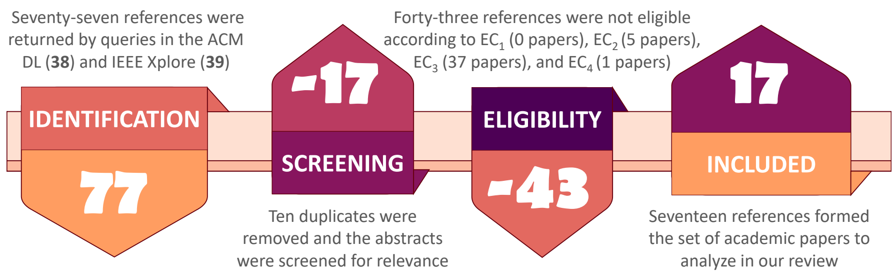

Fig. 1 PRISMA [21] diagram (Preferred Reporting Items for Systematic reviews and Meta-Analyses) showing the results of the identification, screening, eligibility, and inclusion stages of our literature review of scientific contributions found at the intersection of AmI and MR.

with motor impairments, for which the keyword "motor" was used in another sense, e.g., electric motors for vibrotactile feedback for people with visual impairments. For the rest of the papers, we employed the following eligibility criteria (ECs):

- EC_1. *Availability.* The full text is available and the paper is written in English.
- EC_2. *Peer-reviewed academic papers.* We considered only peer-reviewed contributions, such as journal articles and conference papers, and excluded keynotes, workshop papers, book abstracts, etc.
- EC_3. *Focus on MR.* We excluded papers that addressed VR only [12] or systems employing MR devices for other purposes than MR, such as smartglasses being used for eye gaze tracking only [10].
- EC_4. *Focus on AmI.* We excluded papers that did not consider an AmI context.

After eligibility, we arrived at a set of 17 papers relevant to our scope; see Figure 1.

2.2 Measures and Analysis

We extracted the following information from the eligible papers:

- *Contribution type,* for which we considered the following categories: system, technical study, user study, and survey. The system category includes papers that describe an interactive system, application, or device, e.g., [1, 16, 30, 36, 47]. The user study category includes papers reporting the results of an experiment or study involving human participants, e.g., [1, 30, 47]. Papers with technical studies also report evaluations of the presented systems [8, 18, 47]. And survey contributions include detailed discussions of the scientific literature.
- For papers reporting user studies, we extracted information about the total number of participants and the number of participants with motor impairments.
- *Application type* with six categories: navigation, video games, rehabilitation, control of devices, extended motor skill, and other. Extended motor skill refers to technology designed to augment users' motor skills beyond rehabilitation.

- *Attributes of MR* with five categories: number of environments (one and many), number of users (one and many), level of immersion (not immersed, partly immersed, and fully immersed), level of virtuality (not, partly, and fully), and degree of interaction (implicit and explicit), according to the taxonomy of [38].
- *Attributes of AmI* with six categories: sensitive, responsive, adaptive, transparent, ubiquitous and intelligent, following Cook *et al.*'s [6] overview of AmI technology and applications. For systems falling in the sensitive category, sensors—either installed in the environment or held, operated, or worn by users—collect information about the environment, users, devices, and non-digital things. For responsive systems, users' presence and actions in the environment receive corresponding feedback and system action. Adaptive systems consider users' needs accordingly. Transparent systems implement the principle of the disappearance of technology from user perception. Contributions from the ubiquitous category focus on the integration between the physical environment and computing technology. And the intelligence property refers to the complexity of the algorithms running in the AmI environment.

Two researchers individually extracted information from the papers included in our set according to these categories, confronted their codings and classifications, and discussed any differences to reach agreement for each paper and each category. Where agreement was difficult to reach, a third researcher intervened in the classification of those particular cases. We adopted this approach because both MR and AmI concepts do not have clear-cut definitions[3,4] and, consequently, allow ambiguities in the interpretation of systems and applications that implement them.

3 Results

We present in this section the results of our meta-analysis of scientific contributions made by the eligible papers from our set combining AmI and MR technology for applications addressing people with motor disabilities and/or limited mobility.

3.1 Scientific contributions

We identified a total number of 35 distinct contributions in the papers that we surveyed, representing an average of 2.1 contributions per paper (SD=0.9, Mdn=2).

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[3] Speicher *et al.* [38] concluded in their paper seeking a definition of MR: "So, what is Mixed Reality? The answer is: it depends. MR can be many things and its understanding is always based on one's context. As we have shown in this paper, there is no single definition of MR and it is highly unrealistic to expect one to appear in the future" (p. 12).

[4] Regarding AmI, Cook *et al.* [6] noted: "Ambient Intelligence has been characterized by researchers in different ways. These definitions [...] highlight the features that are expected in AmI technologies: sensitive, responsive, adaptive, transparent, ubiquitous, and intelligent" (p. 278), while Sadri [31] remarked that "Most authors broadly share similar views of the features required for AmI applications [...] The key features here are intelligence and embedding" (p. 36:2).

The most frequent contribution type was *systems*, found in all of the 17 papers from our set [1–4, 8, 9, 14, 16, 18, 20, 23, 30, 36, 37, 45–47] and representing 48.6% of all of the 35 identified contributions, followed by *technical studies* (52.9% of the papers and 25.7% of the contributions) [2, 18, 20, 23, 30, 37, 45–47], and *user studies* (47.1% of the papers and 22.9% of the contributions) [1, 2, 8, 9, 18, 30, 37, 47], respectively; see Figure 2, top left for a visual summary.

3.2 Application types

We classified the systems from the literature according to their purpose, as follows: *navigation*, *video games*, *control of devices*, *rehabilitation*, *extended motor skills*, and *other*. Most of the systems implemented navigation assistance via sensors mounted on the wheelchair [23, 37, 47], applications to assist with wheelchair control [3, 36], and interactive maps [1, 8, 9, 14]. A percent of 41.2% of the papers described systems for motor rehabilitation [3, 4, 16, 18, 30, 45, 46], and 41.2% presented video games [2, 9, 14, 16, 18, 30, 46]; see Figure 2, top right. In some cases, video games were designed for rehabilitation purposes. Two papers proposed devices to extend motor skills [20, 45], and one paper focused on controlling large displays [14].

3.2.1 User studies and participants

Eight papers (47.1%) reported system evaluations and user studies [1,2,8,9,18,30,37, 47]. The number of participants varied between 2 and 215 (M=39.0, SD=10.0), and six studies [1, 2, 8, 9, 18, 30] involved participants with motor impairments (M=13.5, SD=9.4 participants); see Figure 2, middle for an overview.

3.2.2 Attributes of AmI environments

All of the systems presented in the papers that we examined fulfilled the *sensitive*, *responsive,* and *adaptive* attributes of AmI environments. We identified the *ubiquitous* attribute in eleven papers (11/17=64.7%) [2–4, 16, 20, 23, 30, 36, 37, 46, 47], followed by *intelligence* (41.2%) [4, 14, 16, 20, 23, 30, 37], and *transparent technology* (23.5%) [1, 8, 9, 18], respectively. Overall, the systems that we analyzed featured between 3 and 6 attributes of AmI (M=4.3, SD=0.6, Mdn=4); see Figure 2, middle.

3.2.3 Attributes of MR environments

We extracted information about the *number of environments, level of immersion and virtuality*, and *degree of interaction* [38] to evaluate the attributes of MR systems presented in the papers identified in our literature review. *Number of environments* refers to the number of physical and virtual environments to which users have access,

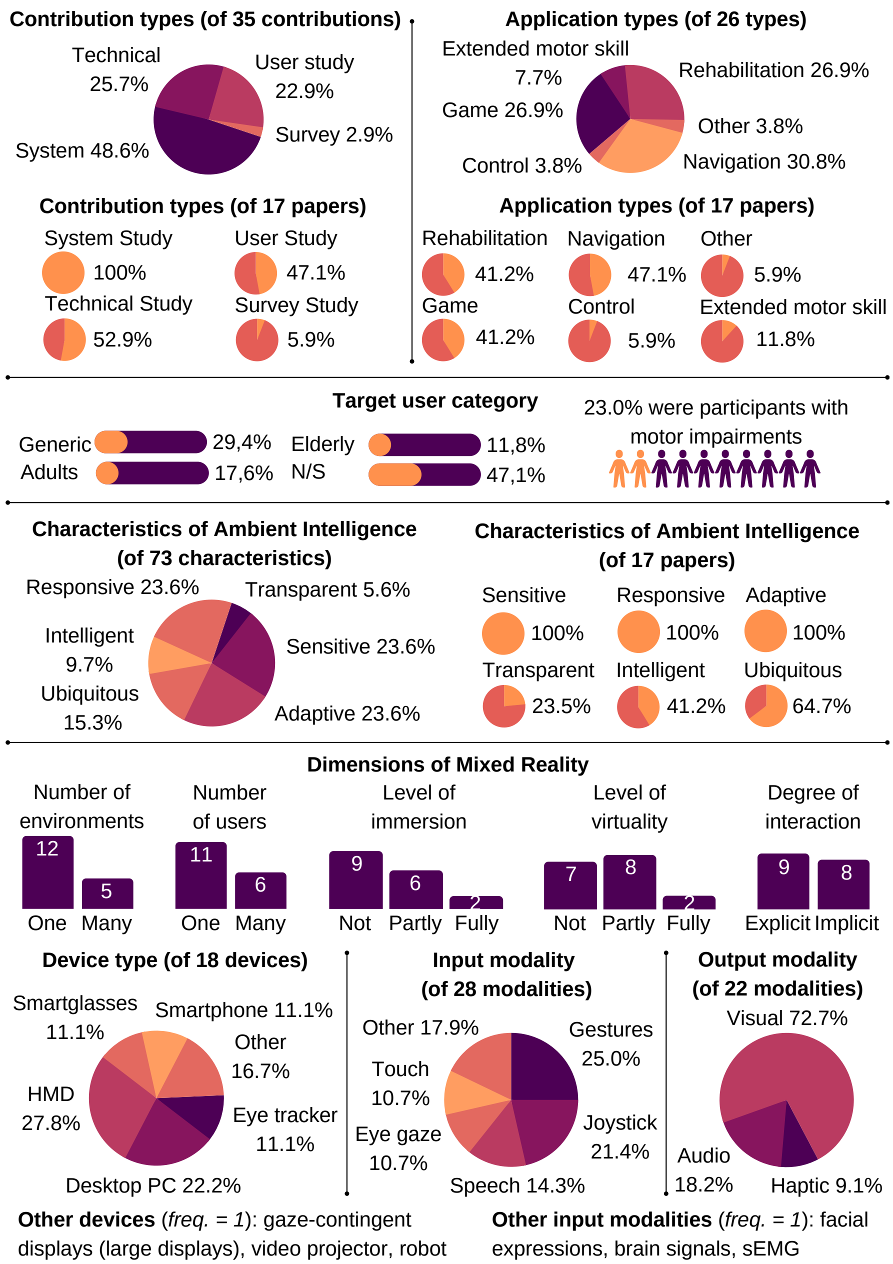

Fig. 2 Scientific and technical contributions, application types, target users, and summary of AmI and MR attributes of the seventeen papers examined in our literature review.

for which we considered multiple environments when users had individual access to the same system [3, 9, 18, 30, 45]; however, for most of the papers (12/17=70.6%), only one environment was available [1, 2, 4, 8, 14, 16, 20, 23, 36, 37, 46, 47]. *Level of immersion* measures user engagement in the MR world [38]. We considered users not immersed if the system displayed only simple notifications about the state of the environment (9/17=52.9%) [1, 3, 8, 9, 18, 20, 23, 36, 37]; we identified six papers (35.3%) [4, 14, 16, 30, 46, 47] for which user immersion was partial, i.e., the systems provided real-time notifications with virtual content; and the level of immersion was full in two papers [2, 45] since users were completely detached from the physical world; see Figure 2, middle. *Level of virtuality* refers to the amount of virtual content presented to the user [38]. We found eight papers implementing partial presence [14, 16, 18, 30, 36, 37, 46, 47] and two implementing full presence [2, 45]. Lastly, we identified explicit interaction in 52.9% of the papers [1, 2, 8, 9, 14, 18, 30, 45, 46] and implicit interaction for the rest [3, 4, 16, 20, 23, 36, 37, 47].

Figure 2, bottom completes our meta-analysis with information regarding the type of devices (e.g., smartphones, smartglasses, HMDs) and the input and output modalities identified in the papers that we surveyed. The most frequent input modality was represented by gestures (25.0%), while user feedback was mostly visual (72.7%).

4 Conclusion

Our analysis of the scientific literature revealed a small number of papers addressing research in the synchrony between AmI and MR for people with motor disabilities. The systems described in the literature favored some AmI attributes, such as sensitivity, responsiveness, and adaptivity, while other attributes were addressed to a less extent. Also, most of the interactions implemented by the systems that we surveyed focused on gesture input and visual feedback, and the most frequently used devices to render MR to users in AmI environments were HMDs and desktop PCs. Regarding user studies, only 23% of all of the participants (81 out of a total of 351) had motor impairments and/or limited mobility. These results show that assistive technology that combines the attributes of AmI and MR environments is still incipient, but we believe opportune towards designing and engineering systems that, in the synchrony between these two research areas, can adapt better to users' needs and be anticipatory of and responsive to those needs to render users more effective in both the physical and virtual world. Future work will examine further the complementary attributes of AmI and MR to enable universal access to information and services in smart environments with practical applications, such as consumption of interactive media [39, 42] in the context of ARTV [43] and the accessibility of AR, MR, and VR technology [15, 17, 25] for people with motor impairments and/or limited mobility, but also focus on using dedicated software architectures for smart environments [32, 33] and toolkits for MR [26, 27] to implement practical applications.

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