Leveraging Sensorimotor Realities for Assistive Technology Design Bridging Smart Environments and Virtual Worlds

Radu-Daniel Vatavu
MintViz Lab, MANSiD Research Center
Ştefan cel Mare University of Suceava
Suceava, Romania
radu.vatavu@usm.ro

ABSTRACT

Sensorimotor Realities are a newly introduced concept of a computer-based physical-virtual reality with distinctive quality dimensions with respect to virtual, augmented, mixed, and extended reality environments. In this landscape of computer-based environments, Sensorimotor Realities center on the user's sensorimotor abilities that undergo mediation in the conjunction of ambient intelligence and physical-virtual worlds. In this work, we explore the application of Sensorimotor Realities to assistive technology and accessible computing research and practice. To this end, we conduct a targeted literature review of scientific contributions published at CHI, UIST, ASSETS, and VRST—four venues where assistive technology and accessibility research for smart environments and virtual worlds has been traditionally disseminated,—and show how they can be characterized from the distinct perspective offered by the conceptual space of Sensorimotor Realities. Moreover, we present design opportunities for assistive technology enabled by the dimensions of the Sensorimotor Realities conceptual space, accompanied by examples from the scientific literature.

CCS CONCEPTS

• **Human-centered computing → Accessibility theory, concepts and paradigms**; **Mixed / augmented reality**; **Ubiquitous and mobile computing theory, concepts and paradigms**; **Ambient intelligence**.

KEYWORDS

Sensorimotor Realities, assistive technology, accessibility, accessible computing, extended reality, mixed reality, augmented reality, virtual reality, smart environments, ambient intelligence

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1 INTRODUCTION

Prior work in assistive technology and accessible interactive computer systems has leveraged the technologies of smart environments [27] and virtual, augmented, and mixed reality [15,16,20] for applications that adapt to users' abilities towards increased access to digital information and more accessible interactions in computer-supported environments of many kinds [35]. Recently, the concept of Sensorimotor Realities [47] (SRs) was introduced in the landscape of virtual, augmented, mixed, and extended reality environments to characterize applications and systems designed in the conjunction of ambient intelligence and physical-virtual worlds [45] that mediate users' sensorimotor abilities, i.e., the combined perception of a physical-virtual world and the corresponding motor action in a smart environment. In this paper, we repurpose the SRs conceptual foundations and principles to make the following contributions: (1) A targeted literature review of assistive technology and accessibility research addressing topics about smart environments and virtual worlds, published over a five-year period at CHI, UIST, ASSETS, and VRST, which shows that contributions to accessible computer systems can be effectively characterized from the perspective of SRs; (2) An in-depth discussion of a selected set of prior systems, which reveals new design opportunities enabled by the dimensions of the SRs conceptual space [47], such as using environment augmentation to enrich the user experience of virtual content, combined sensorimotor mediation to provide missing auditory information through haptic stimulation, or complementing virtual content with the constituent elements of an imagined world.

2 AN OVERVIEW OF SENSORIMOTOR REALITIES

We start with a brief presentation of SRs [47], a recently introduced conceptual framework that depicts a new type of a computer-supported reality with distinctive attributes in the landscape of extended reality (XR), along virtual, augmented, and mixed worlds. SRs capitalize on users' sensorimotor abilities applied in computer-supported worlds, which are mediated by the technology of smart environments along the following six dimensions (see Figure 1 for an illustration):

D_1. *Sensory mediation* specifies the nature and amount of mediation of user perception taking the form of *amplification, extension, diminution,* or *reduction.* For example, *amplification* enhances stimuli perception of the same nature (e.g., see-through glasses for better color perception), while *extension* enhances perception beyond the natural possibilities of the human body (e.g., night vision with infrared glasses).

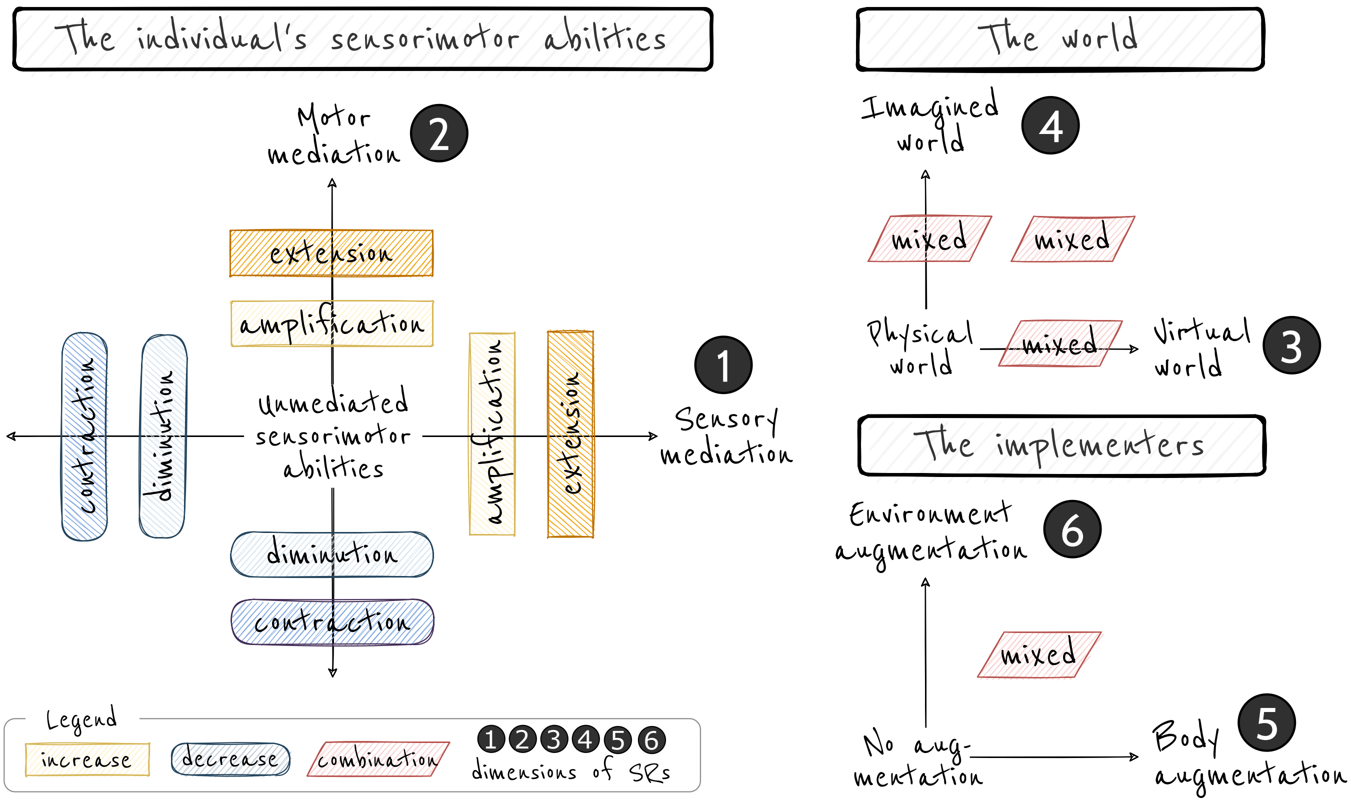

Figure 1: Conceptual space of Sensorimotor Realities, adapted from Vatavu [47].

D$_2$. *Motor mediation* represents the nature and amount of mediation of the user's motor action, with four categories: *amplification, extension, diminution,* and *reduction.* For example, *diminution* restricts motor action (e.g., limits on the extension of the finger to simulate a motor impairment), while *contraction* refuses the motor ability altogether.

D$_3$. *Virtuality* is Milgram and Kishino's [23] continuum, describing augmentation of the physical or virtual world with elements from outside it, e.g., augmented reality.

D$_4$. *Imaginarity* is the degree in which mental imagery is needed for effective operation in the world.

D$_5$. *Body augmentation* specifies the use of wearable devices to mediate sensorimotor abilities from within the self.

D$_6$. *Environment augmentation* specifies the integration of computer technology in the physical environment for mediating users' sensorimotor abilities from external to the self.

SRs were introduced in the context of ability-mediating design [47], i.e., the design of computer devices, applications, and systems that mediate users' sensorimotor abilities through large world coverage (physical, virtual, and imaginary) and instrumentation of the body and/or the physical environment. In this paper, we show how SRs can also be used for assistive technology and accessibility research. To this end, we adopt a two-stage approach. In the first stage, we characterize prior systems from the assistive technology and accessible computing research using the dimensions of the SRs conceptual space; see Section 3. In the second stage, we discuss in detail a selected set of systems, for which we propose new design opportunities with SRs; see Section 4.

3 SENSORIMOTOR REALITIES FOR CHARACTERIZING CONTRIBUTIONS IN ACCESSIBILITY RESEARCH

We use in the following the SRs conceptual space (Figure 1) to analyze prior systems from the assistive technology and accessibility research literature using the perspective of the sensorimotor abilities they have addressed. An important aspect for conceptual spaces is how useful their quality dimensions are for concept description, formation, and induction [12] as a geometric way of representing knowledge [4]. In our case, usefulness refers to the capacity of the users of the SRs space—researchers and practitioners—to employ its dimensions for characterizing and comparing systems, but also for informing new system designs. In the following, we exemplify the descriptive and evaluation power of the SRs space by revisiting, from the perspective of SRs, prior work addressing sensorimotor abilities and users with impairments, published over a five-year period (2017-2021) at CHI, UIST, ASSETS, and VRST—four venues where such research has been traditionally disseminated. The following query:

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Abstract: ((((augmented OR mixed OR virtual OR
extended OR mediated) AND reality)
OR (AR OR MR OR VR OR XR)) AND (access* OR impair*
OR disab*))
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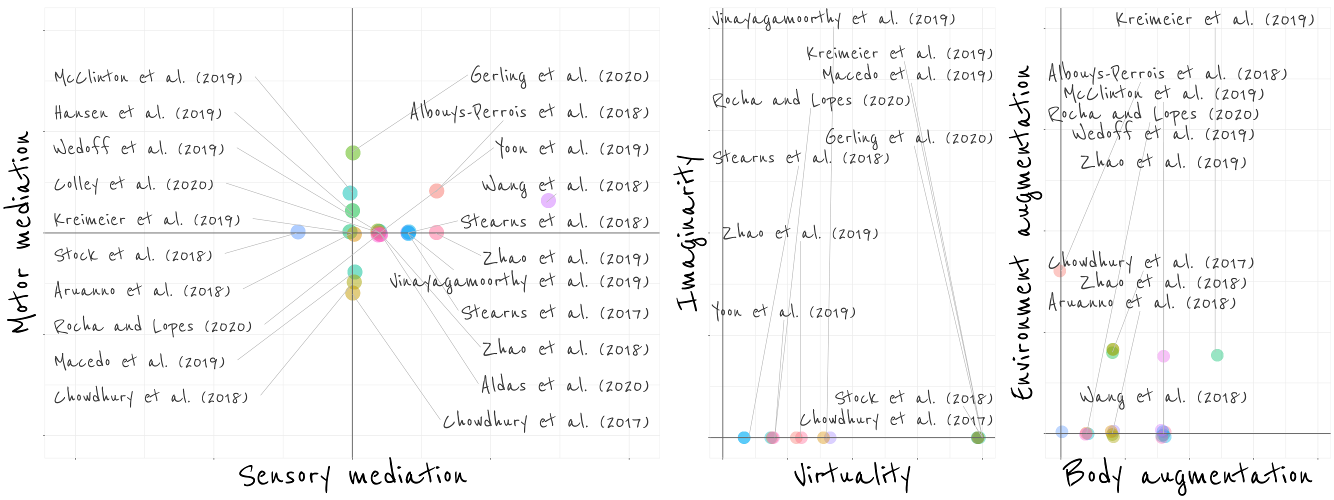

Figure 2: Illustration in the SRs space of prior systems [1,3,7–9,13,14,18,21,22,31,38–40,42,50–52,54–56] that focused on sensorimotor abilities in various physical-virtual worlds. *Note:* the author-year information is listed in the left figure for all of the systems from our sample, but only a selection is shown in the middle and right figures for legibility reasons.

ran in the ACM Digital Library identified 69 references from CHI, 15 from UIST, 14 from ASSETS, and 27 from VRST. We read the abstracts and filtered out references not complying with the following eligibility requirements: (1) the reference must be an academic, peer-reviewed paper, e.g., we removed entries representing workshop and proceedings descriptions; (2) the reference is about assistive technology and/or accessible computing, e.g., we removed papers for which the words from our query were used in other contexts; (3) the reference describes at least one system that uses XR technology and explicitly positions as an augmented, mixed, or virtual reality system, e.g., we removed user studies, literature surveys, opinion papers, etc., such as Andrade *et al.* [2] that conducted interviews with users with visual impairments to inform development of more inclusive AR/VR games, but did not present a system. After the screening process, we arrived at N=21 eligible systems, which we characterized using the dimensions of the SRs space, as follows.

The motivations behind the systems described in the papers from our set were diverse, from assistive technology to enable navigation in the physical world [56] to enabling wheelchair users to explore in VR activities difficult to access physically [13], or enabling navigation of VR environments for people with visual impairments by transferring their white can skills into the virtual world [55]. Given their focus on specific abilities, these contributions can be readily positioned in the $D_1 \times D_2$ domain of the SRs space; see Figure 2, left. For instance, Vinayagamoorthy *et al.* [50] presented a HoloLens system that displayed a sign language human interpreter next to the TV set to mediate hearing loss with AR visualizations for viewers with hearing impairments. We placed this system on the D_1 axis in the region of *sensory amplification* since the ability to hear was enhanced by mediating technology. Zhao *et al.* [56] introduced an AR system designed to assist people with low vision with stairs identification, highlighting, and navigation. We placed this system on the D_1 axis at the right of Vinayagamoorthy *et al.*'s since it provided more sensory amplification by employing both visual and aural augmentations. Note that the positions of these two systems on the D_1 axis reflect an ordinal ranking only, i.e., [56] implements more sensory amplification compared to [50], without an actual numerical quantification of the amplification. On the motor axis (D_2), we placed McClinton *et al.*'s [22] system enabling users with Amyotrophic Lateral Sclerosis to control a brush cursor via EEG input for drawing in VR. In that system, *motor amplification* was achieved by mediating an existing ability to move in the virtual world. We also placed Gerling *et al.*'s [13] VR video games for wheelchair users on the D_2 axis, but above McClinton *et al.*'s system, since the former enabled more modalities to mediate locomotion in VR via arm gestures, head gestures, and automated locomotion controlled by the game, respectively. We found only one system that implemented *sensory diminution*: Stock *et al.* [40] introduced a VR system for the simulation of cataract, glaucoma, and age-related macular degeneration effects, which we positioned at the left of the origin on the D_1 axis. We also found systems that implemented *motor diminution,* as follows. In Macedo *et al.*'s [21] VR game, users sit down on a chair and control a virtual character in a wheelchair in the game. In Chowdhury *et al.*'s [7,8] VR games, an actual wheelchair was used, which amplified the degree of *motor diminution* for the user and, thus, Chowdhury *et al.* position lower on the D_2 axis compared to Macedo *et al.*. Finally, two systems [1,51] implemented both sensory and motor mediation. Albouys-Perrois *et al.* [1] employed video projections, audio feedback, and tactile tokens in a spatial AR system designed to mediate interactions with physical maps for users with visual impairments, achieving thus both *sensory* and *motor amplification.* Wang *et al.* [51] implemented *sensory extension* in the form of remote vision for users with motor impairments by displaying in a HMD the stream of a video camera mounted on a robot, but also *motor amplification,* where the ability to control eye movements was mediated for VR navigation.

Figure 2, middle also shows the systems identified from our set of papers positioned in the $D_3 \times D_4$ domain according to the type of XR world they implemented. All of the systems are arranged along the virtuality axis (D_3) as they represent either AR [1,3,31, 38,39,50,54,56] or VR worlds [7–9,13,14,18,21,22,40,51,52,55]. We arranged these systems on D_3 according to the amount of virtual content they implemented and the primary world that was augmented, following Milgram and Kishino's [23] interpretation of the Reality-Virtuality continuum. For example, Stearns *et al.* [38,39] implemented software magnification for users with low vision, Zhao *et al.* [56] implemented visual enhancement of stairs, and Vinayagamoorthy *et al.*'s [50] system displayed human avatars performing sign language interpretation next to a physical TV. Thus, we arranged these systems in this order on the D_3 axis since they implemented increasingly more virtual content, while all of the systems that implemented VR worlds were placed at the right end of the D_3 axis, respectively.

Figure 2, right shows the systems positioned in the $D_5 \times D_6$ domain of the SRs space. Most of the systems employed wearable devices to deliver sensory and/or motor mediation to users, while considerably fewer [1,8,13,14,18,52] used environment augmentation. We positioned systems in this domain according to the number of devices, sensors, equipment, etc. employed to augment the body and/or the environment. For instance, Vinayagamoorthy *et al.* [50] used a HMD, Macedo *et al.* [21] employed a HMD and controllers, while Kreimeier *et al.* [18] employed a HMD, controllers, and headphones. Thus, these three systems are arranged in this order on the D_5 axis as they enable increasingly more augmentation of the user's body. Some of the systems [8,13,14,18,52] employed both on-body devices and environmental sensors, such as Wedoff *et al.* [52], who used Kinect to track the position of the player's body in the Virtual Showdown game, and Kreimeier *et al.* [18] that employed a treadmill to enable locomotion in VR.

Although our search and discussion of the scientific literature on this topic are by no means exhaustive, the sample of papers serves our goal to illustrate the feasibility of SRs to characterize different computer-based systems addressing sensorimotor abilities in both smart and virtual environments. Next, we show how the SRs conceptual space can also inform new design opportunities for assistive technology and accessible interactive computer systems.

4 SENSORIMOTOR REALITIES FOR INFORMING NEW CONTRIBUTIONS IN ACCESSIBILITY RESEARCH

To complement our results from the previous section, we discuss in detail a selection of prior work that addressed sensorimotor abilities, including visual, motor, hearing, and tactile [3,19,25,33,48,50], which we analyze using the dimensions of the SRs conceptual space. We selected these prior contributions according to the different sensorimotor abilities they targeted, but also according to the different venues where they were disseminated. In the following, we use these examples to highlight how the lack of an appropriate paradigm for positioning contributions addressing various sensorimotor abilities has constrained authors to contextualize their works in the framework of other research areas, mostly as applications of AR, MR, and VR. Moreover, we show how framing these contributions from the perspective of SRs is not only felicitous, but also leads to new design opportunities.

4.1 Sign language interpreter for viewers with hearing impairments

Vinayagamoorthy *et al.* [50] presented a system for delivering sign language interpretations to TV viewers with hearing impairments, and positioned their contribution as AR: "We present an exploratory study in which we collect participant responses ... to three methods of delivering sign language interpretations of a factual documentary on TV: the traditional picture-in-picture 'in-vision' method and two AR enabled methods using the designs of two AR interpreters proposed in a previous paper" (p. 2) and "We evaluate two designs of AR interpreters which could be used as part of a sign language interpreted experience in a TV+HoloLens system" (p. 3). One of the findings was that "At the beginning of the study, we thought it [the TV+HoloLens system] had the potential to enrich the experience of viewing signed content. However, that is not how all participants felt ... Personalisation is key to delivering useful TV augments. Our results show that the demands made by deaf viewers on the sign-language service are very individual" (p. 10).

This first example is interesting for at least two reasons. First, the authors present their contribution in the area of AR, but use the HoloLens HMD, a device introduced by its manufacturer in the context of MR.[1] A possible explanation for the authors' choice of terminology is that the virtual avatars were designed as 2D graphics instead of 3D models and there was no interaction between the virtual interpreters and the physical world.[2] Second, the work is about enhancing hearing abilities or substituting existing abilities with visual feedback in the form of a virtual interpreter, for which Vinayagamoorthy *et al.* conclude that personalization is key to deliver TV augmentations that are useful to viewers. These two observations suggest a contribution that, although using the technology of AR/MR, may benefit from repositioning in a new paradigm. Since abilities are addressed directly (the target audience is people with hearing impairments of various kinds—profoundly deaf, deaf or with hearing impairments, hard of hearing, uncorrected hearing impairments [50, p. 5]), the framework provided by SRs can characterize the contribution effectively and support the conclusion regarding the personalization of TV augmentations.

According to the dimensions of the SRs conceptual space, the TV+HoloLens system implements sensory mediation via extension (D_1), operates in the mixed physical-virtual world (D_3), and is supported by a wearable device (D_5). Thus, the system takes advantage of three out of the six possible dimensions of SRs. However, by framing the contribution in SRs, new design possibilities become available. For example, the physical environment can be augmented along dimension D_6, e.g., via video projections [44] following the "Augmented world/Conventional TV" scenario for AR television [49], to alleviate field of view limitations of HoloLens that were signaled by the participants from [50]. Also, combined sensorimotor mediation along dimensions D_1 and D_2 could provide missing sound information through haptic stimulation [11], e.g., on a smartwatch or the TV remote control [41]. Interactive avatars could elicit responses via gesture interaction along dimension D_2

[1]https://www.microsoft.com/en-us/hololens.
[2]For differences between AR and MR such as these, that depart from Milgram and Kishino's [23] original definition of MR, we refer readers to Speicher *et al.*'s [37] examination of "what is mixed reality?."

through gamification to foster bimanual coordination tasks, known for beneficial effects on the development of motor skills in children with hearing impairments [36].

4.2 Simulating Cataracts in AR/VR

Krösl *et al.* [19] introduced CatARact, a system for simulating cataract vision with the goal to "create a system that provides a more complete, accurate and immersive simulation than previous work, to help people without cataracts to better understand how people with cataracts view their environment" and "to train medical personnel, as well as to increase the understanding and empathy of relatives of cataract patients" (p. 683). In a user study, "for each participant, [the authors] simulated only their individual symptoms experienced with their cataract-affected eye" (p. 688). One conclusion was that "different lighting conditions influence the perception of cataract symptoms" (p. 691) and, thus, improvements of the CatARact system are needed.

SRs can offer a better framing for this contribution with increased potential for future development, as follows. The authors of CatARact proposed their contribution as an application in the area of AR, likely because of their use of AR/VR technology to implement the system. According to the dimensions of SRs, CatARact implements sensory mediation by diminution (D_1) in a mixed physical-virtual world (D_3) rendered with the HTC Vive Pro HMD (D_5). By positioning CatARact in the SRs space, several possibilities for future development emerge beyond those mentioned in [19]. For instance, motor mediation along dimension D_2 can be implemented, where users from the target audience experience the effect of the visual impairment during physical manipulation of objects and interaction in the world, since congenital cataract may have the effect of delayed motor functioning [6]. This new dimension can increase the realism of experiencing other visual abilities along with corresponding coping strategies equally experienced when interacting with the world under cataract, with the potential to increase the effectiveness of training for medical personnel and the empathy of relatives of cataract patients, the two categories of CatARact users. Moreover, the physical environment could be augmented along dimension D_6 to correct for the negative impact of different lighting conditions observed in [19], for instance via smart ambient lighting [43] in the context of smart environments.

4.3 Wearable Mixed Reality for People with Neurodevelopmental Disorders

Aruanno *et al.* [3] introduced HoloLearn, an application designed for HoloLens "to help people with NDD [neurodevelopmental disorders] learn how to perform simple everyday tasks in domestic environments and improve autonomy" (p. 40) by featuring a virtual avatar that gives hints during the execution of various tasks. The authors placed their work in the context of MR, referred to as "the richest form of Augmented Reality" that, in contrast to AR, "provides a stronger merging of real and virtual reality. Instead of just seeing a set of digital elements overlaid on the view of the physical world, in MR the user can interact with an artificial environment, where the surrounding physical space, realistic rendering of physical materials, and digital objects, all coexist and communicate in real time" (p. 40). Among the results of an exploratory study with participants with disorders from the NDD spectrum, the authors noted: "Because each individual with disabilities has unique characteristics, the educational value of a technology for this target is strongly related to its ability to be personalized to each users' evolving needs. HoloLens experiences should be conceived from the very start with this requirement in mind, as occurred in HoloLearn" (p. 48).

This paper presents a contribution in assistive technology supported by MR. While the contribution can be described as an application of MR, SRs can offer a better framing. Especially since MR seems to have been chosen as the supporting technology because of the authors' conceptualization of MR as "strong AR" [37], characterized by advanced environment understanding and interactions, both between the user with the virtual avatar and the virtual objects with the environment.[2] In the SRs space, HoloLearn implements enhanced perception and motor action (D_1 and D_2) in a mixed world (D_3) rendered by HoloLens (D_5). The other dimensions of SRs bring several opportunities to develop future versions of the system. For instance, the findings of the exploratory study [3] revealed that some of the participants with NDD experienced challenges in using HoloLens, including eye gaze input, air gestures, and cursor following, which required support from the caregivers. The authors discussed possible improvements for HoloLearn to address these issues, such as a different color for the cursor and longer periods of familiarization with the HMD. However, a simple alternative readily suggested by dimension D_6 is room-level interactive projection mapping [17] that does not require wearing devices for users that experience such accessibility challenges.

4.4 An Exoskeleton that Miniaturizes Grasp

Nishida *et al.* [25] introduced HandMorph, a hand exoskeleton that approximates the experience of a smaller grasping range, meant for product designers "to momentarily change their grasp into that of a child while evaluating a toy prototype" (p. 573). When motivating their work, the authors related and compared their prototype to VR alternatives, e.g., "unlike other size-illusions based on virtual reality, HandMorph achieves this in the user's real environment, preserving the user's physical and social contexts" and "unfortunately, while previous embodiment devices are powerful, they only work in VR and not in the user's social and physical environment" (p. 565). A study revealed that users' grasping ability was perceived to decrease when using HandMorph, while the sense of ownership was low.

Although the technical contribution of this work can be analyzed in the area of exoskeleton research [34], its motivation as an alternative to VR as well as its focus on empowering users with modified abilities for grasping suggest that a framing in terms of SRs may be more felicitous. According to the dimensions of SRs, HandMorph implements diminution along the motor dimension (D_2) by creating the illusion of an imagined world (D_4) via on-body augmentation (D_5). By integrating the other dimensions of SRs, new opportunities become readily available for HandMorph. For instance, sensory mediation along dimension D_1 could complement modulated grasping ranges by presenting the user with differences in visual perception between children and adults [28]. Along the environment dimension D_6, grasped objects could alter their physical properties, such as weight, volume, and shape [24,30], to further complement the new experience of mediated grasps. Along dimension D_3, a smaller grasping range could be experienced in relation to grasping in VR [32] or interacting via everyday "proxy" objects [10].

5 CONCLUSION

We used Sensorimotor Realities, a recently introduced concept for computer technology designed to mediate perception and motor action in the conjunction of ambient intelligence and virtual worlds [46], to examine system contributions in assistive technology and accessible computing research. We showed that not only the SRs conceptual space can be effectively used to characterize and compare such systems—i.e., it has descriptive and evaluation power,—but also that it can inspire design opportunities for new assistive technology, i.e., it presents generative power. Based on our preliminary results, we propose future work on examining the SRs conceptual space more closely for assistive technology and accessible interactive computer systems in the context of smart environments (i.e., integration of technology in the physical environment) and wearable computing (i.e., body augmentation using computer technology) combined with virtual worlds, including further theoretical developments, but also technical solutions informed by the design perspectives offered by SRs. A larger-scope literature review, which would include other venues and a longer time period, is recommended to better understand the usefulness of SRs for describing research contributions in assistive technology and accessible computing. Finally, we propose future work that compares the relative qualities of the SRs conceptual space, centered on computer technology designed to mediate sensorimotor abilities, to those of other design approaches centered on the user, such as user-centered design [26], ability-based design [53], bodystorming [29], and anthropology-based computing [5], to mention a few, towards a rich, comprehensive, multi-faceted framework for designing more accessible interactions in computer-based environments with the technologies of ambient intelligence and virtual worlds.

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